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EVALUATION OF THE RUTTING POTENTIAL OF ASPHALT MIXES USING THE GYRATORY TESTING MACHINE

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ABSTRACT

This report presents the study made on an evaluation of rutted pavement samples and laboratory compacted mixes using the Gyratory Testing Machine (GTM) as described in the ASTM D-3387. The objective was to investigate the GTM parameters and ways with which procedures and criteria could be developed for evaluation and screening mixes with rutting potential.

The study involved testing samples taken from a section of Hwy 401 experiencing severe rutting and comparing results with those obtained on laboratory mixes of good stability. Additionally, based on relationships between GTM parameters and densities produced by various compactive efforts e.g. vertical pressure and number of revolution, a set of interim criteria and design procedures were developed. The relationship between Marshall stability and GTM stability properties as well as the degradation potential of GTM compaction under high number of revolutions and pressures were also examined.

The results so far obtained demonstrated that the GTM has the ability to quantify stability properties based on engineering principles. Recommendations are made for further study with the machine before full implementation of the GTM requirements in future designs and specifications.

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1. INTRODUCTION

In 1979, slight wheel track rutting was observed on the eastbound driving lane of the Hwy. 401 between Oshawa and Trenton. By 1982 the rutting was so severe, measuring some 32 mm in depth, that immediate treatment was required in six different areas between Hwy. 28 and 45.

An investigation was conducted in that year, prior to the treatment of these areas, to determine the cause of the problem and whether the deformation occurred below the asphalt pavement layers i.e. base failure. The investigation involved sawing and removal of a narrow strip of asphalt pavement in one location and coring of others to obtain samples for testing in the laboratory. Also, samples of granular base and subbase materials were taken from the sawn strip for testing. The profiles of different layers of the pavement were measured. The investigation found that the causes of the problem were the poor stability and marginal V.M.A. properties of the HL-1 and HL-4 mixes used for the resurfacing contract in 1975. The situation was aggravated by the rapid increase in truck traffic and axle loads during the intervening years. Similar subsequent investigations of the other sections of Hwy. 401 confirmed these findings.

It was recognized that there were some 35 km (22 miles) of pavement along Hwy. 401, mainly on the eastbound driving lane, between Ajax and Trenton which were effected by the rutting. Complete rehabilitation of these ruts would cost millions of dollars. Also, an estimated addtional 60 km (40 miles) of Ontario's highways carrying similar traffic as Hwy. 401 could be affected by the same problem in time. The recent development of the 'super-single' truck tires will further intensify the problem; it is reported (7) that the life of the pavement will be drastically shortened

due to the greater pressure exerted on asphalt mixtures and the pavement structure.

2. SEARCH FOR A METHOD

The main concern which arose from this problem was how a designer could suitably design mixes that would withstand this type of traffic conditions. The present Marshall design method is generally recognized by designers as not adequate and the criteria cannot be reliably used as indicators for defining rutting resistance requirements for heavy traffic conditions. On the other hand, with the present asphalt technology, one can compose mixes that can be very stable and will perform well under heavy traffic. However, the dilemma here is that one always runs the risk of overdesigning a mix for which good aggregates may have to be trucked in at high cost while some local aggregates might well be suitable. Therefore, what is needed is a test method which can be used to design mixes reliably with properties of the right magnitude for the traffic conditions under consideration.

In view of the above discussion, a search was made for a suitable method which could evaluate and design mixes that would perform in heavy traffic conditions, especially in respect to the strength properties of a mixture. The method and test procedures should simulate as accurately as possible in the laboratory the state of stress that will exist in the service environment. In addition, the points for consideration are that the equipment should be relatively inexpensive, readily available, simple to use and quick to produce results so that it will also lend itself for use as a rapid field control test.

After reviewing different methods, including the Hveem and the triaxial tests, it was found that the ASTM D-3387 method developed by J. L. McRae of the U.S. Corps of Engineers (presently President of Engineering Developments Co. Inc.) was a good candidate. This method involves the use of an equipment called "Gyratory Testing Machine" (GTM). This report presents the study made on the use of this machine on evaluation of asphalt mixes.

3. THE GYRATORY TESTING MACHINE (GTM)

The GTM combines the compaction with the shear testing of a mix in a single operation. The machine is designed for use on soils, base course materials and bituminous paving materials (1). It has been demonstrated by McRae (1,6) that kneading compaction of samples produces stress-strain properties that are more representative of the actual compacted soil or asphalt material structure i.e. as it occurs in the field, than an impact hammer type of compaction e.g. Marshall compaction. Also, it is suggested (1) that the machine can be used as a "dynamic consolidation" testing device in that a vertical pressure equivalent to that expected in the field can be applied on a sample to simulate the compaction action of the pavement materials under traffic.

Figure 1 shows a sketch of the GTM and the cross section through the gyratory mechanism. The machine consists of four main parts - the loading ram, the gyratory mechanism, the wall friction measuring device and the measuring indicators.

During the compaction testing, the vertical pressure on a preheated loose sample held in a mold is maintained at a constant by the upper and the lower hydraulic ram heads. The upper head acts against the roller

bearings and is free to slide while the lower head is fixed. The position of the mold chuck is set by two fixed rollers acting on the flanged part of the chuck. The adjustable lower roller is held at the selected angle (usually 1 degree) during the operation of the machine. The upper roller stays in an essentially fixed elevation when using the oil-filled cell. There is an option of using the compressible air-filled cell which permits direct adjustment in the gyratory angle as the stress varies. The function of the oil-filled cell is to respond to the pressure developed by the resistance of the sample to the shearing action; as the sample offers greater resistance to the induced stress, the pressure on the oil-filled cell increases. Since the mold is clamped in the mold chuck, any gyratory motion generated by the upper and the lower rollers as they travel around the flange is transmitted to the mold through the mold chuck. As a result, a shear strain is continuously imparted to the mixture in the mold while it is compacted by the gyratory kneading mechanism.

The shear displacement or gyratory angle is recorded graphically on a "Gyrograph" (Figure 2). The gyratory angle is used to obtain the "gyratory indices".

The temperature of the sample in the mold is maintained by the thermostatically controlled heating element surrounding the mold chuck. Details of the machine and test method can be found in ASTM D-3387.

4. SCOPE OF STUDY

This study investigates the procedures and criteria with which rut resistant mixtures can be designed and evaluated using the Gyratory Testing Machine (GTM) for pavements with heavy traffic volume and service

requirements. This involves the following objectives:

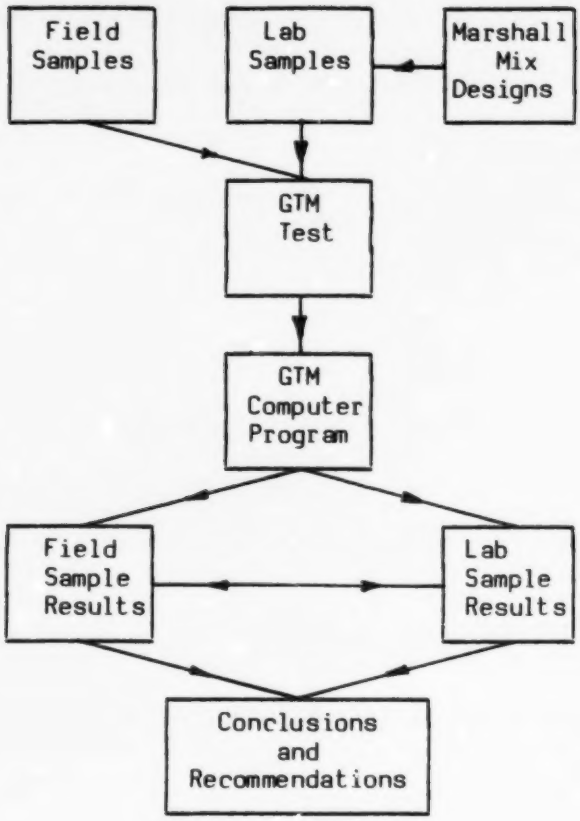
a) to evaluate the significance of different GTM parameters obtained from the type of mixes used in Ontario
b) to determine if there is any degree of relationship between Marshall stability and the GTM parameters
c) to determine if GTM test parameters can differentiate mixes that are susceptible to rutting
d) to recommend design criteria and future development works

As large amounts of data were generated by the tests, a computer program was developed to compute, analyze and compile the results.

The other factor investigated was the degradation of aggregates of mixes with extended cycles of compaction and at high compaction pressure (e.g. >900 kPa). This is to determine if there is any significant change in the gradings as compared to the originals gradings.

5. EXPERIMENTAL APPROACH

As very little is known of the machine in respect to its capability, significance of results generated and, in general, how the GTM can best provide design information for assessment of asphalt mixes, an extensive program was therefore initiated to acquire the answers to many of the unknown factors. The approach to this study can be illustrated by the following flow chart:



It is clear that the ultimate decision on using the GTM for the purpose of mix design will rest on whether asphalt mixes designed by the method and meeting the set of criteria based on the GTM will perform and also that the criteria should be developed on asphalt mixes at densities equivalent to those obtainable in the field. The evaluation of mixes in this study was therefore centred on determining how to obtain such densities with the GTM and the property values at equivalent field densities. The machine variables, such as the loading (i.e. vertical pressure) and duration of compaction (i.e. revolution), that have influence on the change of mix density were systematically evaluated. Comparison of rutted field mixes with laboratory manufactured 'good' mixes (based on experience) was made to establish the GTM properties of the two types of mixes. From these results, a set of GTM criteria was proposed for mix designs. The following summarizes the experiment conducted.

SUBJECT OF INVESTIGATION	MACHINE VARIABLES	PARAMETER RELATIONSHIP	MIX TYPE (# of mix tested)
Loading	V.P. @ 552, 827, 1172, 1379 kPa at 90 rev.	V.P. Sg,R.P., BRD, Eg, GSI, GSF, e, GCF.	Lab: HL-1,2,3,8, DFC (N = 23)
Marshall GTM Relationship	ditto	Marshall Stability Sg, GSI at Marshall density	ditto
Duration to achieve field density	Rev = 90,150 300,400,500 at V.P. = 345 + 1379 kPa	Rev BRD	Field: HL-1,4 (N = 2)
Characteristics of rutted and stable mixes	Rev = 90,150 300,400,500 at V.P. = 827 kPa	Rev GSI, GSF, Sg	Lab: HL-1,4,8, DFC Field: HL-1,3 4,8 (N = 9)
Degradation	Rev = 0, 90, 300, 500 at V.P. = 827 kPa	Gradation	Lab: HL-1,4,8, DFC (N = 4)
GTM Design Criteria	Rev = 90, 150 300, 400, 500 at V.P. = 827 kPa	Rev GSI, GSF, Sg	Lab: HL-1,4,8, DFC Field: HL-1,3, 4,8 (N = 11)

V.P. = vertical pressure
Rev. = revolution
Sg = gyratory shear
R.P. = roller pressure
BRD = bulk relative density
Eg = gyratory compression modulus
GSI = gyratory stability index
GSF = gyratory shear factor
e = gyratory compression strain
GCI = gyratory compactability index
N = number of samples
HL = hot laid
DFC = dense friction course

6. GTM TEST PROCEDURE AND PARAMETERS

In general, the procedure as described in the ASTM D-3387 "Standard Test Method for Compaction and Shear Properties of Bituminous Mixtures by means of the U.S. Corps of Engineers Gyratory Testing Machine (GTM)" was followed. Details of test procedure and other information can be found in the standard and in reference 1. The following briefly outlines the procedure and test conditions that are relevant to this study.

(a) Test Procedure

The procedure included two different sequential steps i.e. the compaction and shear tests, and wall friction test.

For compaction and shear tests, the preheated or freshly mixed sample was placed in the preheated mold and base plate. The entire batch with the mixture was positioned in the machine and the front half of the mold chuck was tightened in position. The vertical pressure was increased to the full compaction level. The sample was then compacted to a predetermined number of revolutions of compaction (e.g. 30, 60, 90 rev. etc). At each stage of the compaction (i.e. each 30 rev.), the machine was stopped and measurements of the roller pressure and vertical sample height were taken.

The final step of the test involved measuring the wall friction between the sample and the mold surfaces. The wall friction was used as a correction for the shear resistance generated in the mixture. This was done by using the two jacks beneath the wall friction yoke provided in the machine assembly.

The gyratory readings from the gyrograph at different revolutions were determined and, with the wall friction value, the different parameters were computed.

(b) Test Conditions

- Sample preparation: the samples were prepared the same way as for Marshall compaction, including temperature and mixing time.

- Roller: the oil-filled roller was used throughout this study.

- Vertical pressure: varying vertical pressure was used, i.e. at 552, 827, 1172 and 1379 kPa (80, 120, 170 and 200 psi). Since most highways under MTC jurisdiction come under the medium or heavy to very heavy categories, it was therefore decided that a V.P. = 1034 kPa (150 psi) would be used for the very heavy traffic whereas a 552 kPa (80 psi) for a medium traffic road. Higher pressures (e.g. 200 psi) were experimented with to gain fuller understanding of the trend of mix properties, and of the capability of the machine.

- Duration of compaction: a series of 30, 60 and 90 revolutions of compaction were performed on the laboratory samples. In order to establish the rate of densification of mixtures for determination of the densities produced in the field, extended cycles of compaction up to 500 revolutions were performed on the field samples. For the degradation test, the extended cycle of 500 revolutions was also run on the laboratory samples.

(c) Parameters

At the initial stage of this study, additional parameters to those mentioned in the ASTM D-3387 were examined. In the latter part, however, only those applicable were evaluated. The parameters are described in detail in reference 1 and their calculation is shown in Appendix II.

i) Gyratory Shear (Sg)
ii) Gyratory Stability Index (GSI)
iii) Gyratory Shear Factor (GSF)
iv) Gyratory Compactability Index (GCI)
v) Gyratory Compression Modulus (Eg)
vi) Gyratory Compression Strain (e)
vii) Roller Pressure (RP)

7. INFLUENCE OF VERTICAL PRESSURE ON GTM PROPERTIES

The effect of different vertical pressure was investigated to establish the trend of the GTM parameters with the change of vertical pressure. The operation manual (1) of the GTM suggested that the vertical pressure used should be representative of the tire pressure experienced on the road for which the mix is designed. However, it can also be interpreted that the vertical pressure should be related to the volume and type of traffic i.e. heavy, medium and light, that is operating on the highway under consideration. Particular attention is given to the truck traffic because the most of the damage to the pavement is due to the high loadings used.

Since the tire pressure of the "super-single tires" likely to be used by the trucking industry is in the area of the 1034 kPa (150 psi), the vertical pressures investigated in this study therefore covered a range from 552 kPa (80 psi) to 1379 kPa (200 psi), representing medium to very heavy truck traffic. As light traffic roads are not expected to have rutting problems, the lower vertical pressure effect was therefore not included in this evaluation.

Some 23 mixes were involved in the evaluation of the influence of the vertical pressure, ranging from the sand mix type (HL-2) to the stony mix type such as the dense friction course (DFC). The grading envelopes of the HL mixes are shown in Table 1. The DFC mixes have a stone content of 45 or 55% consisting of all crushed high quality aggregates with high polishing resistance (i.e. polished stone value greater than 45) for frictional properties. The mixes were some that have been designed and issued for use in different contracts during the year of 1985. The mixes were designed by the Marshall mix design method as described in MTC LS 261 and 263. Duplicate samples of the designed mixes were weighed and tested by the GTM.

The materials used in the mixes are described in Tables 2 to 6 and the type of aggregates coded in the tables is explained in Appendix I. The asphalt cement (A.C.) type was 85/100 penetration grade. The coarse aggregates for the HL-1 and DFC mixes were either traprock or steel slag while the fine aggregates were blendings of natural sand and limestone screenings (for HL-1) or steel slag fines (for DFC). The coarse aggregates for HL-3 and HL-8 were crushed gravel and the fine aggregates

were similar to those used for the HL-1 mixes. The aggregates used in the HL 2 mixes were the same type of fine aggregates as mentioned for the HL 1 mixes.

(a) Gyratory Shear (Sg)

The Sg measures the shear resistance of the material when the specimen is subjected to an imposed load and a degree of strain. It is believed that the Sg is a type of plane strain shear and it is considered more uniform shear strain than is possible in other type of shear tests. The shear resistance parameter gives an indication as to the friction generated by the interparticle contact and interlock, as well as the resistance to shear due to the rheological properties of the binder. The shear resistance is therefore considered one of the most important factors that determines the stability of a mixture to resist deformation.

From Figure 3, the Sg vs Vertical Pressure graph resembles the Mohr's type diagram in that, for any given degree of shear strain, the shear stress is proportionally developed under a normal load. The angle of internal friction and cohesion values could also be obtained for soil and base materials.

The graph shows that good correlation was obtained between the Sg and V.P.($r = 0.98$) when DFC data were excluded from the correlation data. An angle of internal friction of 21% was also obtained. The aggregates normally used in asphalt mixes would have angles of

internal friction between 30 to 40 degrees, depending on the type and gradation of the aggregate and the degree of compaction (9). The DFC mixes behaved differently from the other dense mixes, showing a curve relationship and correlation coefficient (r) of 0.94. This is expected to be due to the nature of aggregates (i.e. crushed and rough surface texture) and the coarse gradation used in the DFC mixes. The lower levels of Sg obtained are seen to be related to the lower interparticle area of contact and the higher void content of the DFC mix as compared with the HL mixes. This tends to suggest that the HL mixes behave similar to soil materials while the DFC simulates coarse base course materials.

(b) Roller Pressure (R.P.)

As the R.P. relates directly to the gyratory shear (Figure 5), it is a quick indicator of the shear resistance of a mix during testing. For this reason, good correlation between the R.P. and Vertical Pressure is expected as shown in Figure 4. A value of r = 0.98 (excluding DFC data) was obtained and an increase in R.P. was resulted with increasing V.P. i.e. similar to the relationship between Sg and V.P..

(c) Bulk Relative Density (BRD)

Figure 6 shows that the DFC mix density stayed at relatively the same level with increased ram pressures. As the DFC mixes are high

stone content mixtures, consisting of all-crushed materials (at 45 to 55% coarse aggregate), the graph tends to confirm the strong particle interlocking nature of the mixes. Once a DFC mix has reached a certain compaction, an increase in loading/compactive effort will not provide further densification, unless the load exceeds the point where large degradation of aggregate alters the matrix and gradation of the mix. The steady level of density also suggests that the DFC type of mix will not have any significant secondary compaction by traffic as would do with other mixes.

The HL-2 appeared to have a similar densification pattern to the HL-1. Between the loadings of 690 kPa (100 psi) and 896 kPa (130 psi), the mixes seemed to have increased in density and then stabilized at the 1034 kPa (150 psi). With further increases in ram pressure beyond the level of 1172 kPa (170 psi), mix density again increased. The initial densification is expected to be due to expulsion of air voids, whereas the increase in density at higher presssure could be the result of slight crushing (see section 10 c on degradation) and re-orientation of aggregates. The crushing occurred when sharp contact points of the aggregates were subjected to high shear stress at higher ram pressure. Both of these mixes appeared to have achieved the equivalent Marshall design density at 827 kPa of vertical compaction pressure.

The densification of HL-3 and HL-8 appeared to follow a linear pattern. The HL-3 being a finer mix densified more rapidly at lower V. P. than the HL-8. With the mixes consisting mainly rounded

aggregates in both the coarse and fine fractions, the mixes are expected to be compacted easier i.e. good workability to near full density with even low compaction load. Also the density does not change significantly with an increase in vertical pressure beyond the initial compaction.

The significance of the relationship between the BRD and V.P. is in providing information on the level of compactive effort that is required to achieve the density occurring in the field. It also gives some idea as to the degree of secondary compaction that can be expected of the different mixes under the traffic compaction. This laboratory-to-field density relationship is discussed in a later section.

(d) Compression Modulus (Eg)

The value of Eg increased with an increase in vertical pressure (V.P.) for all mixes except the DFC mixes (Figure 7). It is apparent that an increase in V.P. will densify the dense graded mixes whereas the same increase in V.P. (i.e. beyond 1034 kPa or 150 psi) will cause crushing of the aggregates in the DFC mixes (see section 10 c). The reduction in the modulus of the DFC mixes may be as a result of the crushing. Also, as compared with the other mixes, the lower stiffness of the DFC mixes is related to the higher void content of the mixtures.

As the vertical ram pressure can be related to the anticipated loading pressure of tires on the pavement surface, it appears that only when compactive effort equivalent to the tire pressure exceeds

kPa (150 psi) will a reduction of the modulus of the DFC mixes occur. However, it is not expected that the tire pressure will be designed at levels higher than 1034 kPa will be experienced in the foreseeable future, although the "super-singles" may just reach that pressure as discussed.

e) Gyratory Shear Factor (GSF)

The GSF is a safety type of index with regard to failure in simple shear for defined loading conditions. A failure has occurred when the shear strength has been exceeded by the approximate theoretical maximum induced shear stress.

Figure 8 shows that with increased V.P.,

- the DFC had an increase in the shear factor as tighter aggregate contact was generated. The GSF reached a maximum at 1034 kPa (150 psi) V.P. and then decreased beyond that point. This tends to suggest that the reduction of shear strength is due to the slight crushing of aggregate at high vertical pressures.

- for the HL-2 mixes, there is an increase in the GSF with increasing V.P. approaching a maximum at the upper limit of the testing pressure of 1379 kPa (200 psi). Due to the higher specific surface of fine aggregates, a finer mix such as the HL-2 tends to have high contact areas and hence improved GSF with increase V.P.. This tends to suggest that this mix is

becoming more stable as the compaction pressure is increased. This is provided that there is sufficient void space in the mix to accommodate the volume of asphalt cement and thus prevent the development of a plastic condition.

- the HL-3 and 8 mixes behaved in a pattern that the GSF tended to decrease to a point (at V.P. of about 827 to 1034 kPa 120 to 150 psi) and then increased to a maximum before decreasing to a level of about 1.14. It is suspected that at low V.P., the aggregates in the matrix dilate as they are moving for their best-fit position. With higher V.P., the aggregate contact improves resulting in higher GSF. The decrease of the GSF beyond the V.P. of 1034 kPa is at a much lesser degree as compared to the DFC's because of the rounded coarse and fine aggregates used in these mixes.

- the HL-1 curve seemed to follow a similar pattern to the HL-8 except that the GSF stayed at a level of 1.05 at V.P. below the 827 kPa value. This again is due to the shape and packing property of the aggregate in the mix.

- by definition, the higher the number of GSF, the better the mix. As GSF is a ratio derived from the Sg, it often provides the trend and not the real value. The GSF alone is therefore not a good indicator of the stability property and is unsuitable for differentiation between mixes with different stabilities.

(f) Gyratory Stability Index (GSI)

The GSI is defined as the ratio of the maximum gyratory angle to the minimum intermediate gyratory angle, at any selected number of revolutions. GSI in excess of unity indicates a progressive increase in plasticity during densification.

One apparent point that shows up in Figure 9 is the gradual decrease of the GSI between 690 and 965 kPa (100 and 140 psi) for the HL-8 mixes and, beyond that, a rapid decrease down to the 0.96 level at 1380 kPa (200 psi). The HL-1 mixes, on the contrary, had a reverse pattern to the HL-8. The obvious difference between the two mixes is the maximum size aggregate and the gradation. The HL-8 has a nominal maximum size of 19 mm and HL-1 is 13.2 mm. The other difference was the type of coarse aggregates used i.e. rounded aggregate for the HL-8 and crushed aggregate for the HL-1. The decrease in stability index of the HL-8 mixes with increased V.P. beyond the 965 kPa level tends to suggest that the difference in coarse aggregate types as well as the maximum size was the cause of the difference between the curves. Also it confirms the general believe that larger stone size in a mix will result in higher stability.

The other three mixes exhibited an optimum of GSI = 0.985 at V.P. = 965 kPa (140 psi) with low stability or high GSI below and above the optimum.

(g) Gyratory Shear Strain (e)

The curves in Figure 10 again highlighted the difference in the use of aggregate types in the asphalt mixes evaluated. The all-crushed

type of mixes such as the DFC (or to a large extent the HL-2) seemed to produce greater strain than other mixes with rounded aggregates with increase in V.P.. The downward side of the DFC curve indicated densification whereas the upward side indicated some crushing and repositioning of aggregates with, again, the optimum at about the 965 kPa V.P. area. The higher strain means more crushing had occurred in the DFC mixes (section 10 c).

(h) Gyratory Compactibility Index (GCI)

The index gives an indication as to how easily a mix can be compacted under certain compaction conditions. The higher the index number the easier the mix is to compact. Figure 11 clearly indicates that the DFC mixes were the most difficult to compact due to the all-crushed aggregates used. The order of compatibility of different mixes (viz. HL-2, HL-3, HL-1, HL-8 and DFC) shown in Figure 14 under V.P. = 690 kPa confirms what has been observed based on past experience. The HL-8 appeared to have changed to a more workable mix with an increase in V.P. i.e. became easier to compact as density improved.

In general, there is an increase in the shear strength, roller pressure, bulk relative density and gyratory compression modulus with the increase in vertical pressure. The increase is due to densification of mixtures leading to closer particle contact and interlock. While all the parameters have characterized the trend and behaviour of the mixes with an increase in vertical load, the gyratory shear shows good promise of quantifying the stability properties of different mixes.

The parameters have consistently shown that the DFC mixes behaved differently from the other mixes because of the use of high all-crushed aggregates. However, it will be shown later that the range of densities produced by the range of vertical compression pressures employed were denser than normally encountered in the field. The vertical pressures studied mainly aim at providing information and trends of mix behaviour, as was originally planned. The following sections discuss the parameters at density levels attained by Marshall compaction as well as by traffic.

8. RELATIONSHIP BETWEEN MARSHALL AND GTM PROPERTIES

Since very little is known about the use of the GTM, it is desirable to establish if the GTM properties have any relationship with the Marshall stability values. A perfect correlation cannot be expected since the two methods of compaction are entirely different. The gyratory machine produces compaction by a kneading process compared to the sharp impact tamping of the Marshall compaction hammer.

In order to have any meaningful comparison between the values obtained from the two methods, it is necessary to evaluate the GTM and Marshall properties produced from the same range of density values. As it is commonly known that Marshall densities resemble those eventually produced on the road after some years of trafficking, studies of mix property relationships between the two methods were concentrated in the area of similar Marshall density.

From Figure 6 and Tables 2 to 6, it seems that equivalent Marshall density can be achieved by using the GTM at vertical pressure equal to 827 kPa (120 psi) after 90 revolutions of compaction. The GTM results

plotted in Figures 12 and 13 were the values extrapolated from Tables 2 to 6 at the different vertical pressures of equivalent density values to those obtained from Marshall compaction.

The GTM values examined were the Gyratory Shear (Sg) and Gyratory Stability Index (GSI). They were selected after reviewing the different parameters that are likely to have any relationship with the Marshall stability.

(a) Marshall Stability vs Sg: Figure 12 shows that the Marshall test ranked the different mix types in the order that is expected of the mixes e.g. HL-2 at the lower end and DFC at the higher end of the stability range. However, the graph shows mixes with similar stability could have different gyratory shear values, or vice versa. While no relationship between the Marshall stability and Sg is not expected to exist, it appears that mixes with high stability tend to have high gyratory shear.

At the minimum stability requirement level of about 8,900 N for traffic volume greater than 5 000 AADT, a Sg value of 193 kPa (28 psi) is obtained from the graph. It appears that, based on the results of HL-2, there is a reasonable linear relationship existing between the Sg and Marshall stability at the range of 4,000 to 12,000 N.

(b) Marshall Stability vs Gyratory Stability Index (GSI): Figure 13 shows that there is absolutely no relationship between the two factors, despite the fact that both share the same "stability" terminology.

9. CHARACTERISTICS OF GTM PROPERTIES OF RUTTED PAVEMENT MATERIALS

Before the GTM can be used as a design tool, it is necessary to determine if the machine can discriminate between poor and good mixes. Also it is important to know the parameters and criteria with which good or poor stability mixes could be characterized and identified.

In order to provide for such information, laboratory mixes (Table 6) of good stability based on experience were made and tested with the GTM. The results were compared with samples taken from four separate locations of severely rutted highways. One of the sites was the section of Hwy. 401 that had been investigated and reported in MI-56 (2). Two of the other sites were on different areas of the Hwy. 401 eastbound lane (Figure 14) and the third site was on the Bloomington Road - a regional secondary road with heavy truck traffic (Figure 15).

In all cases, rutting occured in the surface and binder courses, i.e. HL-1 and HL-4 (Figure 16) from the three Hwy. 401 sections, and HL-3 and HL-8 from the Bloomington Road. The HL-3 and HL-8 contained some 1.5% of asbestos in the mix. The field sample properties are shown in Table 8. It can be seen that the mixes had very low recompacted Marshall voids (1.5 to 3.1%) and the pavement compaction was near to the maximum density. The gradations of all the mixes were very 'tight' or dense and close to the Fuller maximum density curves (2).

The A.C. content of the HL-3 and HL-8 mixes from Bloomington Road were high (8.2 and 6.6% respectively). This was due to the use of asbestos in the mix designs; hence the Marshall Stability was low and the flows were high (25+).

(a) Relationship of Field and GTM Densities:

For the purpose of evaluation of the samples under realistic conditions, it was first necessary to relate the densities produced in the samples by the GTM with those found in the pavements. While it is tempting to correlate the number of vehicle passes to the revolutions of compaction by the GTM, the traffic pattern and environmental conditions on the road are so diverse that such an exercise is considered difficult and is outside the scope of this study. However, while it is interesting to know the rate of densification under traffic, it is the engineering properties of the mixtures at the ultimate density at or before rutting occurs that should be of importance. This is what the following is attempting to correlate.

Figure 17 shows the rate of densification with increasing number of revolutions for the two different vertical pressures (i.e. 345 and 827 kPa or 50 and 120 psi). The density increased more rapidly with the higher V.P. (827 kPa) than with the 345 kPa V.P.. For both the HL-1 and HL-4 mixes, the densities obtained under the 345 kPa were slightly below the densities achieved under the 827 kPa after some 500 revolutions of compaction. As can be expected, the mixes achieved the near-to full compaction quicker at higher V.P. than at a lower one. Also, with a V.P. = 827 kPa and at 500 revolutions, the densities obtained for both type of mixes were very near to their respective maximum relatively density (MRD).

As shown in Figure 17, the field densities of both type of mixes can be arrived at with only 100 to 140 revolutions of compaction at V.P. = 345 kPa. The densities produced by using a V.P. of 827 kPa

were much higher than those expected from the field for these two mixes, even at low cycles of revolution.However, it is clear that different mix requires different effort to achieve full compaction. These two mixes needed only a low level of compactive effort and therefore is a sign of poor stability. It seems that the compactive effort as represented by the V.P. should not be taken literally to relate only to the tire pressures but also traffic volume experienced on the road.

From Table 9, the average field density is 96.3% of the MRD. With a designed void content of 3 or 4% in the Marshall briquettes, the Marshall density is expected to be about the same level as the field density after 3-5 years service. These data thus reinforce the statement mentioned earlier in the report that Marshall density equals to that of the field density. However, it is stressed that the orientation of the aggregates in the matrix will not be the same as those compacted under field conditions. Since interparticle contact and interlock depend largely on the aggregate orientation. Therefore Marshall samples are not expected to provide the realistic strength values that will quantify the "true" stability properties of mix in the field. In comparison with the GTM kneading compaction, which is more closely simulating field compaction, the GTM properties are more likely to provide values that differentiate asphalt mixtures of various stabilities.

(b) Comparison of Rutted Samples and Laboratory Mixes

Three field rutted mixes and four good laboratory manufactured mixtures were tested and compared. The test involved extended cycles of compaction up to 500 revolutions at 827 kPa (120 psi).

This is to investigate if further compaction would increase the contrast between the good and poor mixes. Three GTM parameters were looked at, viz GSI, GSF and Sg (Table 10), and they are discussed as follows:

(i) Gyratory Stability Index (GSI)

Figure 18 shows that GSI of the rutted field samples increased rapidly with increase in revolutions of compaction while the laboratory mixes stayed relatively at the same level of less than 1.6. The HL-1 laboratory mix appeared to be marginal.

(ii) Gyratory Shear Factor (GSF) and Shear Strength (Sg)

Figures 19 and 20 show that while both values were decreasing rapidly with increasing number of revolutions for the rutted mixes, there was slight increase in the GSF and Sg for laboratory mixes. The laboratory HL-1 decreased gradually confirming that this mix was marginal in stability. (As GSF is derived from Sg, it explains why the GSF graph takes the same shape as the Sg graph).

The above clearly indicates that poor stability mixes behave differently from those mixes expected to have good stability. It appears that, after 200 revolutions of compaction, the parameters were able to differentiate the poor from the good mixes, e.g. for a good mix the GSI should be less than 1.2 and GSF greater than 1.1 or Sg > 276 kPa (40 psi). However, in order to be certain of the properties, an extended revolution of testing is desirable.

10. DEGRADATION OF AGGREGATES UNDER GTM COMPACTION

During the testing for the determination of the rate of densification with increased number of revolutions of compaction and vertical pressure, it was concerned that such test conditions might have degraded the aggregates to the extent that misleading results were being generated. Therefore, degradation testing was carried out to explore this concern.

Four different mixes (i.e. HL-3, 4, 8 and DFC) were selected for testing. Samples were prepared individually with the weight on each sieve proportioned exactly to the designed gradation. The samples were heated and mixed in the normal manner as if for the Marshall Compaction and were then tested by the GTM. Extraction was made on the sample on completion of each test at the planned cycles of compaction by the GTM (e.g. at 0, 90, 300 and 500 revolutions). The results of the extracted gradations are shown in Table 11.

By comparing the original with the extracted gradations, it can be seen that majority of the degradation took place juring the first 90 revolutions of compaction. The gradation seemed to have stablized after the 90 revolutions of compaction. The HL-3, 4 and 8 mixes had degradation ranging from 1 to 3% and the DFC mix had about 4%. As expected, slightly more degradation was observed in the DFC mix due to the augularity of aggregates used. The degradation at various sieve sizes of all the mixes was either near to or just outside the limits allowed for by the standard specification (Form 1150) as illustrated in Table 11.

The degradation study was also conducted on mix gradations with excessively high vertical pressure of compaction e.g. 1172 kPa (170 psi). Two mixes only were tested, one (HL-4) representing the standard dense mixes and the other (DFC) the stony mixes. After 90 revolutions at 1172 kPa of vertical pressure of compaction, the degradation of both mixes appeared to be the same as that previously obtained with lower pressure (827 kPa) after 500 revolutions of compaction. The DFC again turned out to have slightly higher degradation as compared with the other mix. This difference explains the change in the trend of the different curves as discussed in section 7.

11. GTM MIX DESIGN CRITERIA FOR DEFORMATION RESISTANT MIXES

The results so far obtained cannot be used for mix design purposes as they are only related to those mixes evaluated. What is required is a set of criteria that quantifies the engineering properties of asphalt mixtures at similar field densities.

In view of this, the three most relevant parameters viz GSF, GSI and Sg were examined in relation to the field densities of samples obtained from the rutted sections of the highway. The GTM properties of the laboratory mixes (Table 10) with known good stability were similarly evaluated and a set of GTM criteria were formulated as follows:

(a) GSI - Figure 21 shows that the rutted mixes seemed to have a substantial increase in the GSI with slight increase in density. The HL-3 mix from Bloomington Road had a GSI value far in excess of the other mixes (i.e. GSI = 2.785) indicating the highly unstable

nature of the mix. On the other hand, the laboratory mixes showed very little increase in the GSI (e.g. below 1.057). The HL-1 (as shown to be marginal from previous evaluation) and the HL-4 field samples also had significant increase in the GSI.

In order to determine the GSI characteristics of stable mixes, the GSI results of the DFC mixes were used as a guide. This is because, based on past experience, the DFC mix has been observed as the most stable of the hot mixes in resisting rutting.

The GSI value for the DFC mix was 1.057 even after the 500 revolutions of compaction (Figure 21). However, as discussed previously, any additional compaction beyond the 150 revolutions will produce densities well above those normally achieved in the field. Additionally, the field density of the DFC mix cannot be related to the Marshall density despite the statement made before in Section 9a. This is because the density of the DFC achieved by Marshall compaction appeared too dense as compared with the GTM mode of compaction (Tables 7 and 10). This is due to a commonly known fact that Marshall compaction produces excessive crushing of aggregates of stony mixes such as the DFC. Therefore the Marshall density of the DFC mix should not be used to relate to field density. Instead, an estimated 92% of the MRD was adopted, as this is the type of density which is generally obtained on the pavement after few years of traffic compaction. With this estimate, the laboratory DFC mix had a field density of about 2.816 and a GSI of 1.019 is obtained.

It seems that in general, for a stable mix, the GSI value should not be greater than 1.02 at density equivalent to Marshall density. However, the GSI appeared to be not sufficiently sensitive to differentiate the unstable mixes at low revolutions of compaction and extended cycles of compaction are therefore necessary as discussed before. It appears also that the GSI for a stable mix should not exceed 1.06 after 500 revolutions of compaction.

(b) GSF - Figure 22 clearly indicated that rutted mixes exhibited substantial decrease in the GSF while the laboratory mixes had very small change with the GSF. One significant point that can be seen from the curves is that the rutted mixes had actually a decreasing GSF as the mixes were being densified. The laboratory mixes on the other hand showed the contrary. At the field density, the rutted HL 4 mixes seemed to have a GSF value of 1.6 i.e. greater than those of stable laboratory mixes.

From the above discussion, one cannot use a single GSF to identify stable mixes. Rather, it seems that the slope of a curve plotted with density vs GSF should be used. A positive slope indicates a stable mix whereas a negative one shows instability as shown in those mixes obtained from the rutted pavements.

(c) Sg - Figure 23 shows the density vs the Sg relationship at different vertical pressures. The increase in density seemed to be linearly proportional to the increase of Sg after 90 revolutions of compaction. At 1379 kPa V.P., the densities of the HL-1 and 4 mixes were approaching their respective maximum relative densities. With an increase in number of revolutions (e.g. at 500 or greater) mix

densities could also reach to near the maximum as indicated by the dotted lines in the graph.

Based on the field densities, the graph shows that the Sg for the HL-1 mixes was just at the margin of shear failure strength of 152 kPa (22 psi) at a V.P. = 827 kPa (120 psi) as suggested in reference 1. For the HL-4 mixes and the mixes from Bloomington Road, the Sg was at the zero level. Also, from Tables 7 and 8, all the laboratory mixes had Sg values at Marshall density (DFC at 92% of MRD) greater than 290 kPa (42 psi).

The Sg value as evaluated by the GTM method seems to be able to differentiate clearly the poor stability mixes obtained from the rutted pavements. The shear strength failure criteria as suggested in reference 1 appear correct. Also, the compaction effort of a heavy traffic site can be represented by a vertical pressure of 827 kPa (120 psi) which is comparable to the tire pressure of a heavy truck.

Based on the results and discussion so far presented, the following criteria are proposed for design of heavy duty mixes for traffic greater than 5000 AADT per lane (or heavy stop-start traffic area):

GTM Property	Pavement Density Condition	
	Immediately After Construction	Ultimate
	96% of MRD (92% for DFC)	V.P. = 827 kPa after 500 rev.
GSI	<1.02	<1.06
GSF	+ve slope of BRD GSF	>1.10
Sg	Surface course = 155 kPa (25 psi) min. Upper and lower binder course = 140 kPa (20 psi) min.	>276 kPa (40 psi)

The criteria covers the requirements for the two levels of density conditions at which rutting could occur. That is the density level immediately after the construction (e.g. 96% of MRD or 92% for DFC mix) and at full compaction by future traffic (i.e. ultimate). These two levels of density cover the conditions experienced during the service life of the pavement. It is noted that these criteria could be modified with experience and the criteria for the ultimate density condition may only be required in the future. Also, the criteria are established based on experience on mixes investigated and changes may be necessary to fit other conditions.

The following interim procedures are therefore suggested:

(i) Design mixture as per Marshall method to obtain BRD, void content and VMA properties. The stability and flow values should be also determined for reference/checking with specifications (but not as acceptance criteria).

(ii) Determine the MRD and the 96% density level (92% for DFC).

(iii) Weigh out six additional duplicate samples to the designed mix, each to the same mass as the Marshall briquette.

(iv) Perform the GTM test at V.P. = 827 kPa (120 psi) with one sample at each of the 30, 90, 300 and 500 revolutions of compaction, and determine the BRD, GSI, GSF and Sg values after each test.

(v) Perform the GTM test with the remaining two samples at V.P. = 345 and 552 kPa (50 and 80 psi respectively) to 90 revolutions of compaction and similarly determine the BRD, GSI, GSF and Sg values.

(vi) Plot BRD - GSI graph and check GSI limits.

(vii) Plot BRD - GSF graph and check the slope of the curve and 500 rev. limit.

(viii) Plot BRD - Sg graph and check Sg minimum requirements.

12. CONCLUSIONS

This study evaluated the possible use of the GTM for the purpose of evaluation and design of asphalt mixes. The machine has demonstrated its ability to quantify stability properties based on engineering principles. As a result of this study, preliminary proposals on criteria and procedures for mix design have been made. It is clear that they can only serve as an interim guide and further refinement based on future experience is necessary so that such criteria and procedures can be used with confidence.

The following summarizes the findings of this study:

a) The gyratory shear strength, when tested with various vertical pressure produced a graph that resembles the Mohr's type of diagram. This reinforces the fact that shear strength can be reliably used as an engineering property to quantify the stability of asphalt mixes.

b) The roller pressure of the GTM can be used as a quick check on the state of shear strength of a mix developed during the test. It gives a direct read-out and lends itself to use as a quality control tool.

c) In order to evaluate mixes using the GTM, it is important to compare the properties of mixes at expected field density levels.

d) The compression modulus, gyratory shear strain and compactability index did not prove to be useful factors for assessing the stability of mixtures.

e) The gyratory shear factor is judged to be useful criteria only when the slope of the density and GSF curve is known. A positive slope indicates that a mix is stable and vice versa.

f) The gyratory stability index can be used to differentiate mix stability, but it is shown to be not as sensitive as desired. It appears that a stable mix should have a gyratory shear index of less than 1.02 at density level equal to that of Marshall and should not exceed 1.06 after 500 revolutions of compaction.

g) There was no relationship established between Marshall stability and the GTM parameters evaluated.

h) Test results on field samples have shown that the Marshall densities, or about 96% of maximum relative density as determined by Rice Method (ASTM D-2041 or MTC LS-264), approximate to those obtained on the road after several years of trafficking.

i) A compactive effort with a vertical pressure of 827 kPa at 90 revolutions was found to be suitable in producing densities equivalent to the Marshall densities (except for DFC mixes). However, this effort was found to be excessive for the two rutted mixes tested; their equivalent field densities were obtained using a vertical pressure of 345 kPa after about 120 revolutions of compaction.

j) The slight degradation generated by extended cycles of compaction did not seem to affect the test results.

13. RECOMMENDATIONS

As concluded, the GTM offers good potential for adoption as a mix design method for paving mixtures. Further work is necessary before full implementation of the GTM requirements in future specifications. The type of works which are recommended for immediate consideration are:

i) Correlate field and GTM compacted sample densities and stability properties. Samples should be taken from a broad spectrum of highways covering different traffic volumes, truck loads, age, mix types and geographic locations.

ii) Develop GTM design procedure and criteria which are independent of the Marshall mix design method.

iii) Initiate steps to introduce the use of GTM as a field quality control tool as it shows good potential for production of rapid test results.

iv) Perform additional sampling on rutted pavements to verify the proposed criteria.

v) Select at least five contracts for complete design, construction and performance monitoring using the GTM.

Other relevant studies that should be performed to further understand the capability of the machine as follows:

a) Design of DFC mixes by Marshall method should be re-evaluated by using the GTM. This is in light of the degradation caused by excessive crushing of aggregates under the impact of the Marshall hammer compaction.

b) The effect of compaction temperature on the GTM properties of asphalt mixtures should be investigated.

c) The effect of grades of asphalt cement, aggregate type and gradation should be fully evaluated.

d) The mixes that have been evaluated in this report and placed under different contracts should be monitored.

Reference

1) McRae, J.L. "Gyratory Testing Machine Technical Manual", Engineering Developments Company Inc., Vicksburry, Mississippi, 1965.

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3) "Method for Design of Bituminous Mixes", Ontario Ministry of Transportation and Communications, 1986.

4) Tia, M. and Wood, L.E. "The Use of a Gyratory Testing Machine in the Evaluation of Cold-Recycled Asphalt Paving Mixtures", ASTM STP 881, Pavement Maintenance and Rehabilitation, 1985.

5) Kandhal, P.S. "Marshall Mix Design Method: Current Practices", Paper prepared for presentation at the 61st Annual Meeting of the Northeastern States Materials Engineers Association, 1985.

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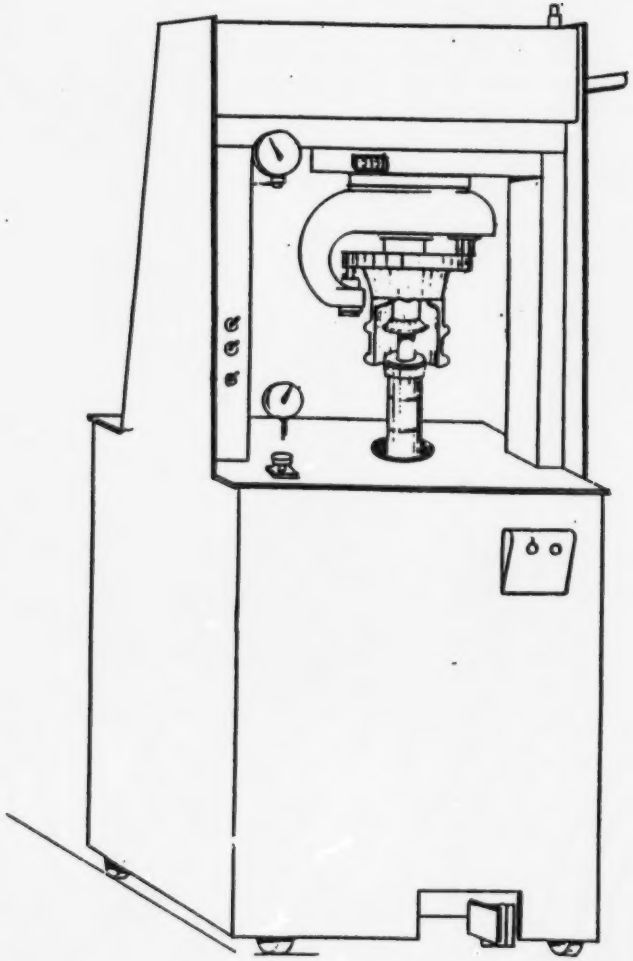
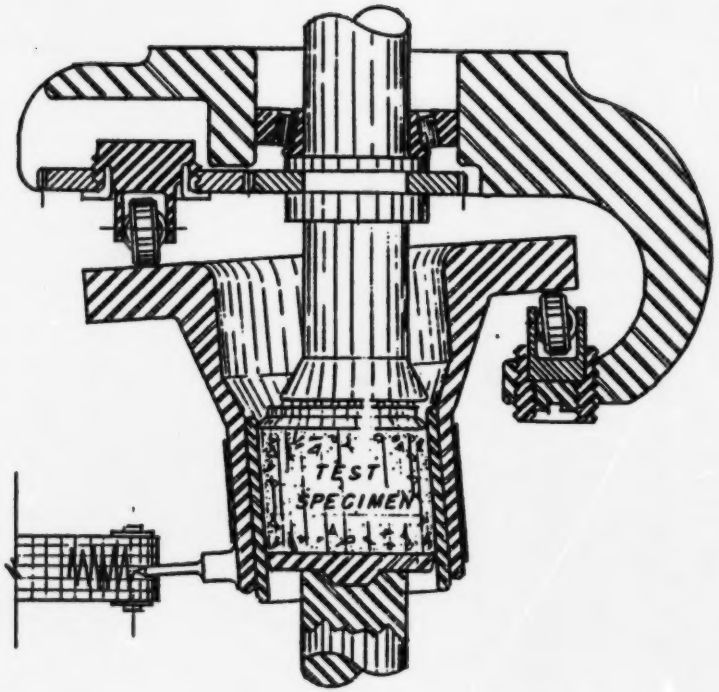
8) Southgate, H.F., Sharpe, G.W., Anderson, M. and Deen, R.C. "Evaluation of Full-Depth Asphaltic Concrete Pavements" Research Report UKTRP-84-21, University of Kentucky, 1984.

9) Forster, C.R. "The Strength of Asphalt Pavements" Proceedings, Association of Asphalt Paving Technologists, Vol. 54, 1985.

10) ASTM D-3387, "Standard Test Method for Compaction and Shear Properties of Bituminous Mixtures by Means of the U.S. Corps of Engineers Gyratory Testing Machine (GTM)" American Society For Testing and Materials Section 4, Vol. 04.03, 1985.

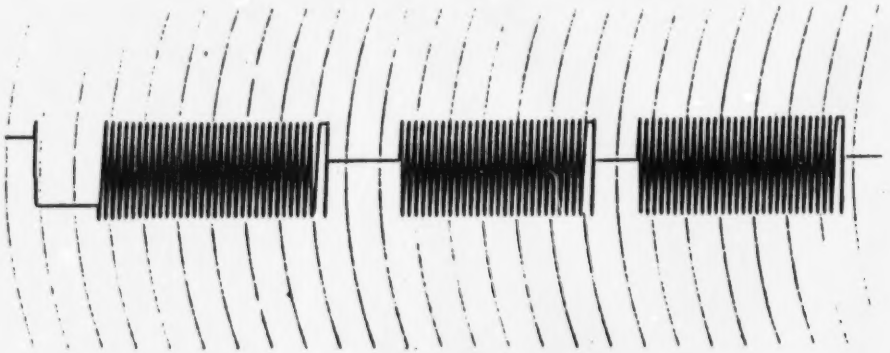


(a) Front View

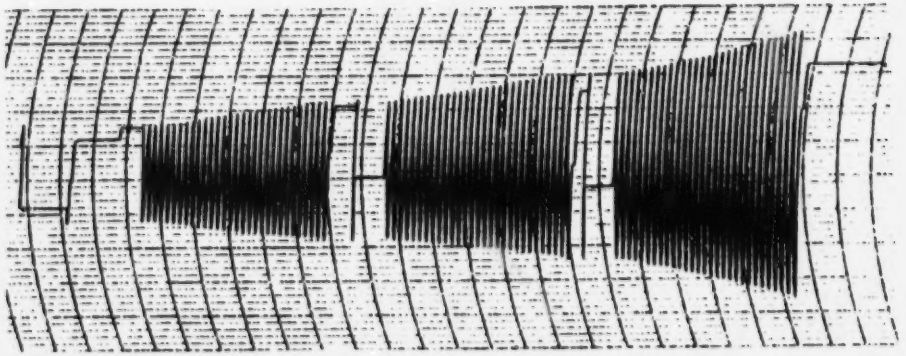


(b) Cross section through the gyratory mechanism

FIG. 1 THE GYRATORY TESTING MACHINE



Hwy. 401, Trench 'B'
HL-4 Binder Course
Vertical Pressure = 120 psi
A.C. Content = 5.1%



Bloomington Road
HL-3 Surface Course
Vertical Pressure = 80 psi
A.C. Content = 8.2%
Asbestos added.

FIG. 2: GTM GYROGRAPH

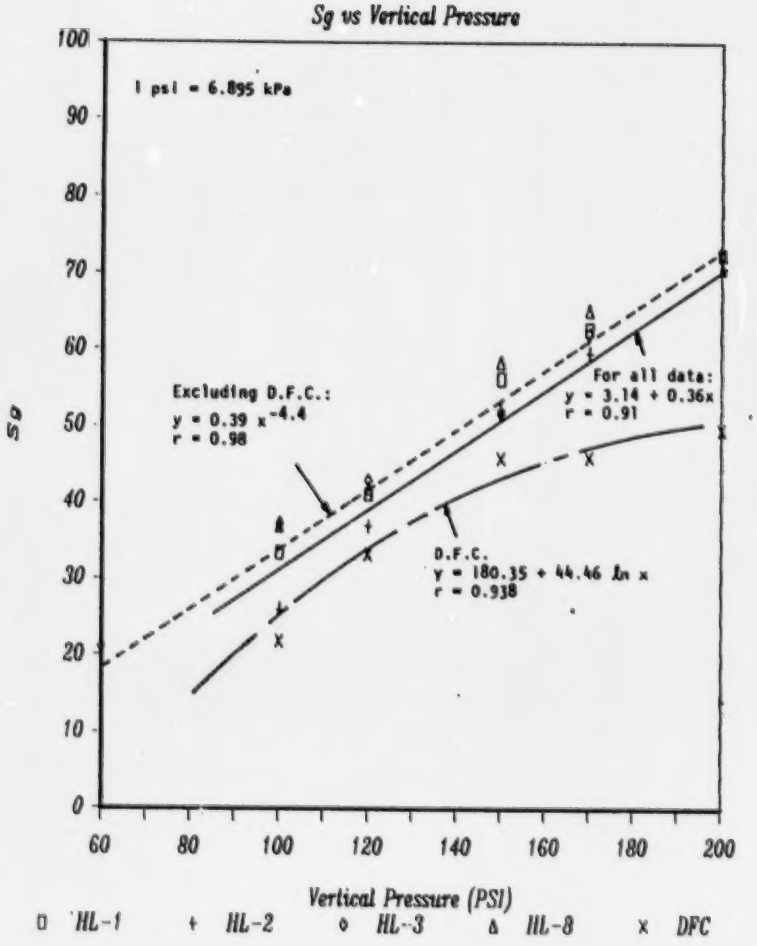

Sg vs Vertical Pressure
1 psi = 6.895 kPa
Excluding D.F.C.:
y = 0.39 x^-4.4
r = 0.98
For all data:
y = 3.14 + 0.36x
r = 0.91
D.F.C.
y = 180.35 + 44.46 ln x
r = 0.938
Sg
Vertical Pressure (PSI)
HL-1
HL-2
HL-3
HL-8
DFC

FIG. 3

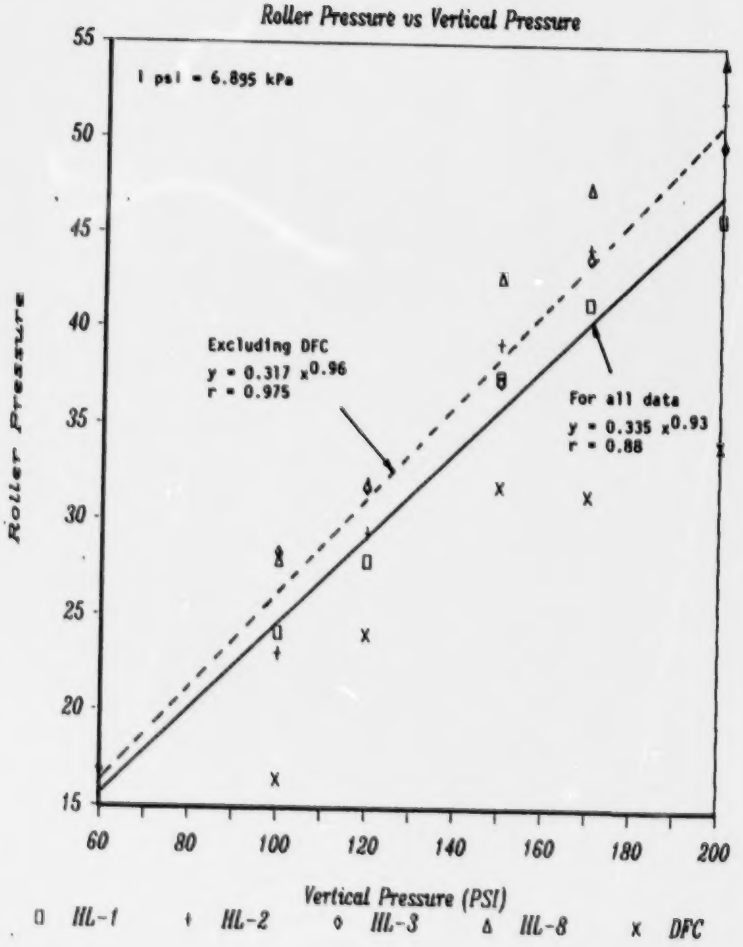

Roller Pressure vs Vertical Pressure
1 psi = 6.895 kPa
Excluding DFC
y = 0.317 x^0.96
r = 0.975
For all data
y = 0.335 x^0.93
r = 0.88
Roller Pressure
Vertical Pressure (PSI)
HL-1
HL-2
HL-3
HL-8
DFC

FIG. 4

FIG. 5

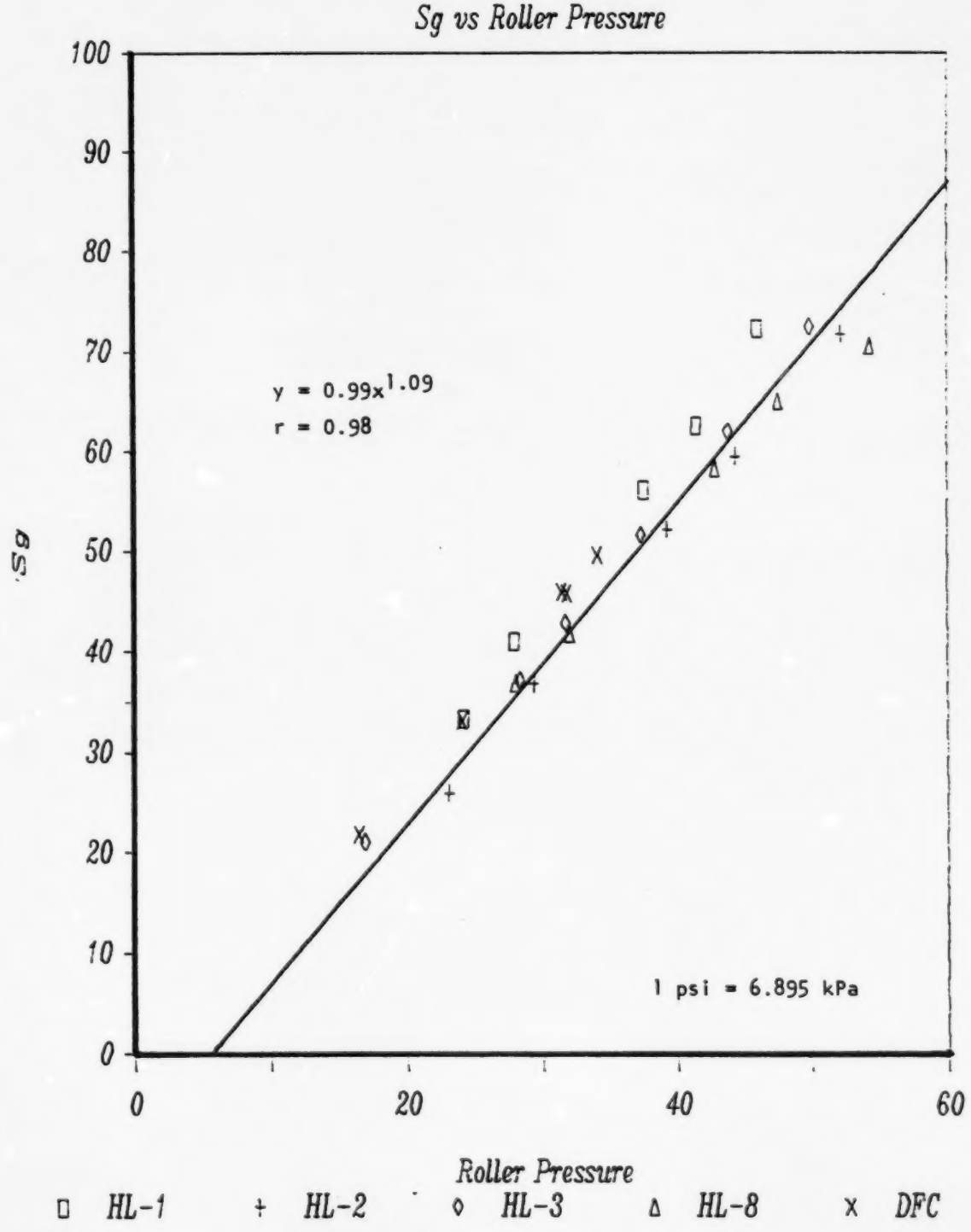

Sg vs Roller Pressure
100
90
80
70
60
50
40
30
20
10
0
Sg
y = 0.99x^1.09
r = 0.98
1 psi = 6.895 kPa
0
20
40
60
Roller Pressure
HL-1
HL-2
HL-3
HL-8
DFC

FIG. 6

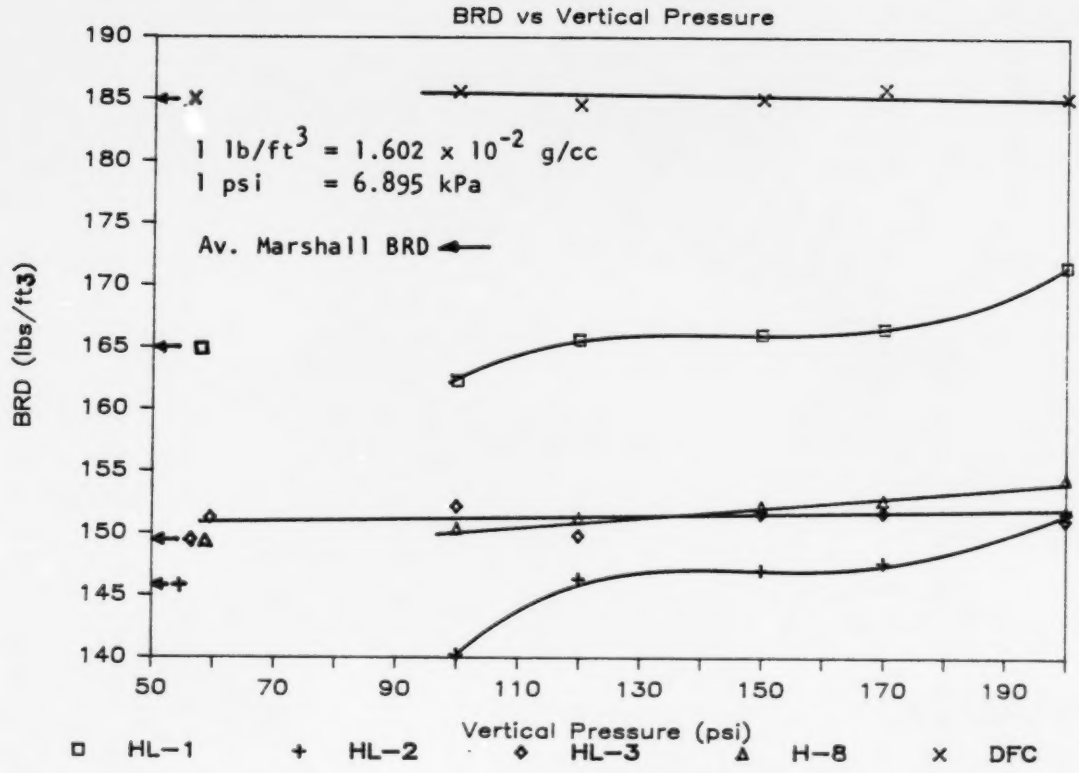
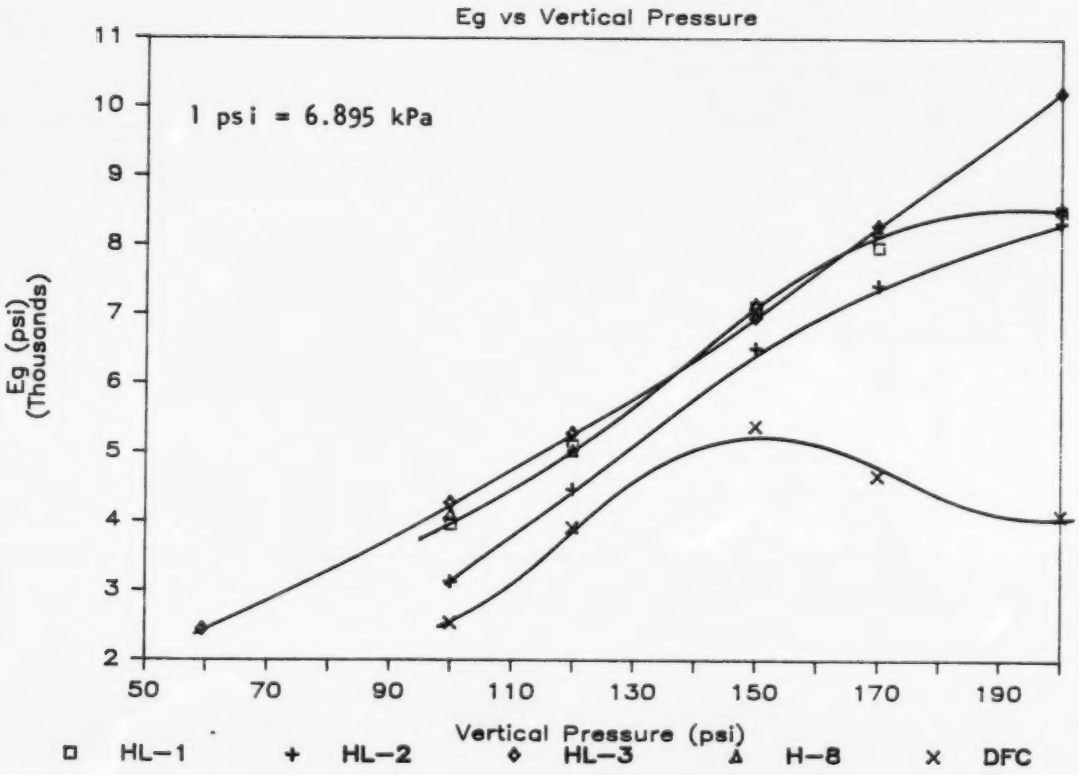

BRD vs Vertical Pressure
1 lb/ft3 = 1.602 x 10-2 g/cc
1 psi = 6.895 kPa
Av. Marshall BRD
BRD (lbs/ft3)
190
185
180
175
170
165
160
155
150
145
140
50
70
90
110
130
150
170
190
Vertical Pressure (psi)
HL-1
HL-2
HL-3
H-8
DFC

FIG. 7


Eg vs Vertical Pressure
1 psi = 6.895 kPa
Eg (psi) (Thousands)
11
10
9
8
7
6
5
4
3
2
50
70
90
110
130
150
170
190
Vertical Pressure (psi)
HL-1
HL-2
HL-3
H-8
DFC

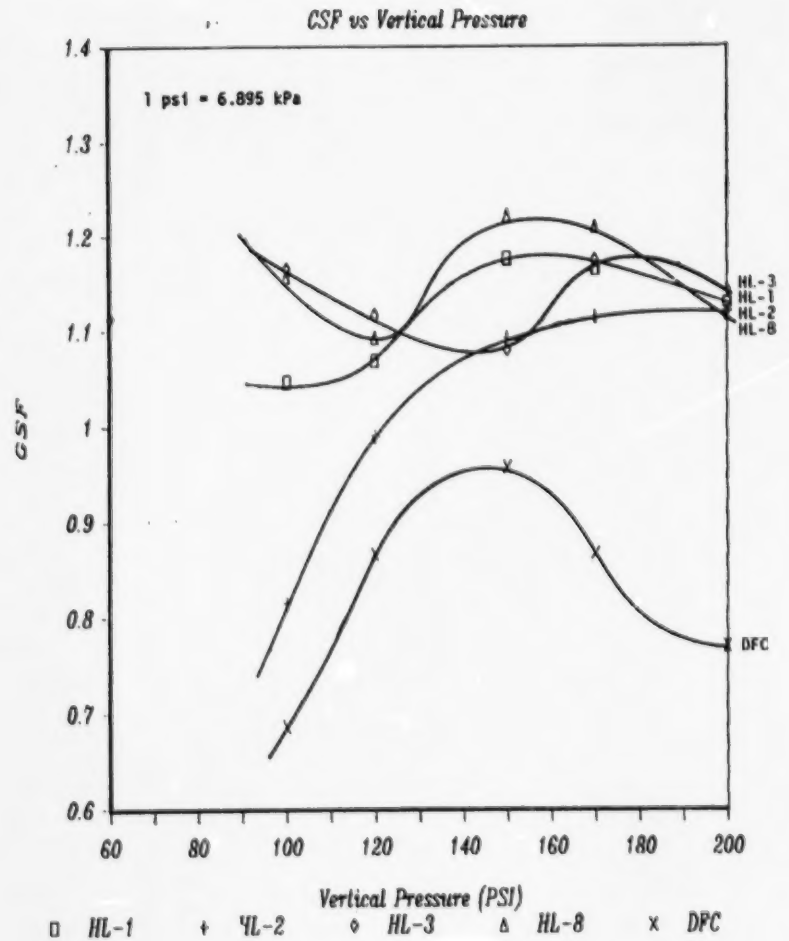

CSF vs Vertical Pressure
1 psi = 6.895 kPa
GSF
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
60
80
100
120
140
160
180
200
Vertical Pressure (PSI)
HL-3
HL-1
HL-2
HL-8
DFC
HL-1
HL-2
HL-3
HL-8
DFC

FIG. 8

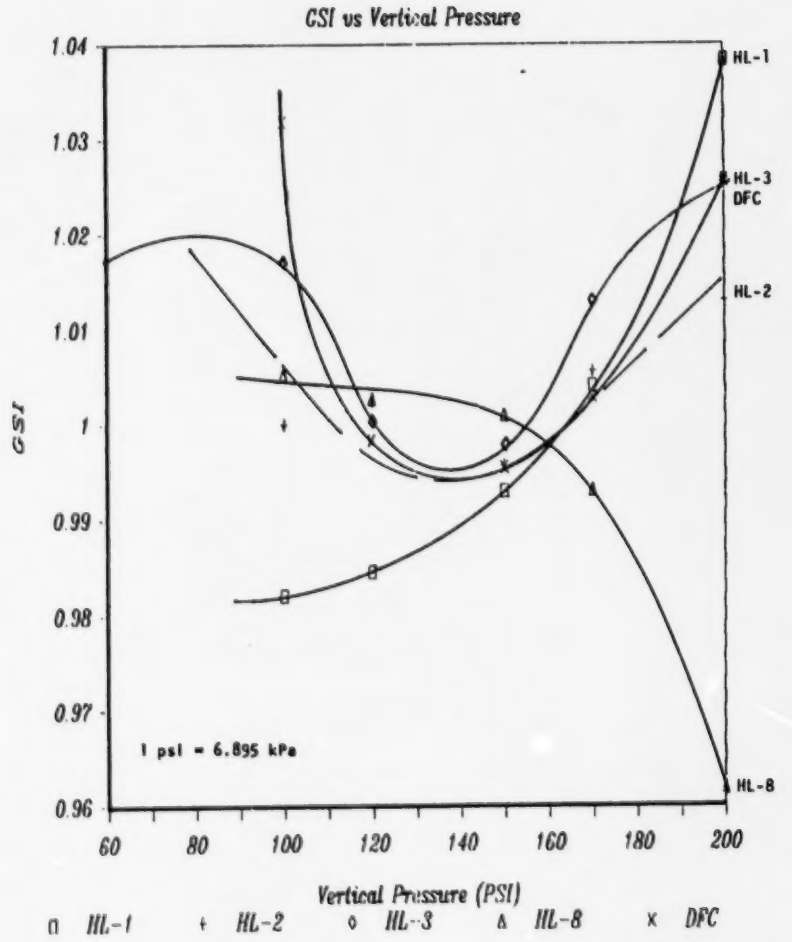

CSI vs Vertical Pressure
1 psi = 6.895 kPa
GSI
1.04
1.03
1.02
1.01
1
0.99
0.98
0.97
0.96
60
80
100
120
140
160
180
200
Vertical Pressure (PSI)
HL-1
HL-3
DFC
HL-2
HL-8
HL-1
HL-2
HL-3
HL-8
DFC

FIG. 9

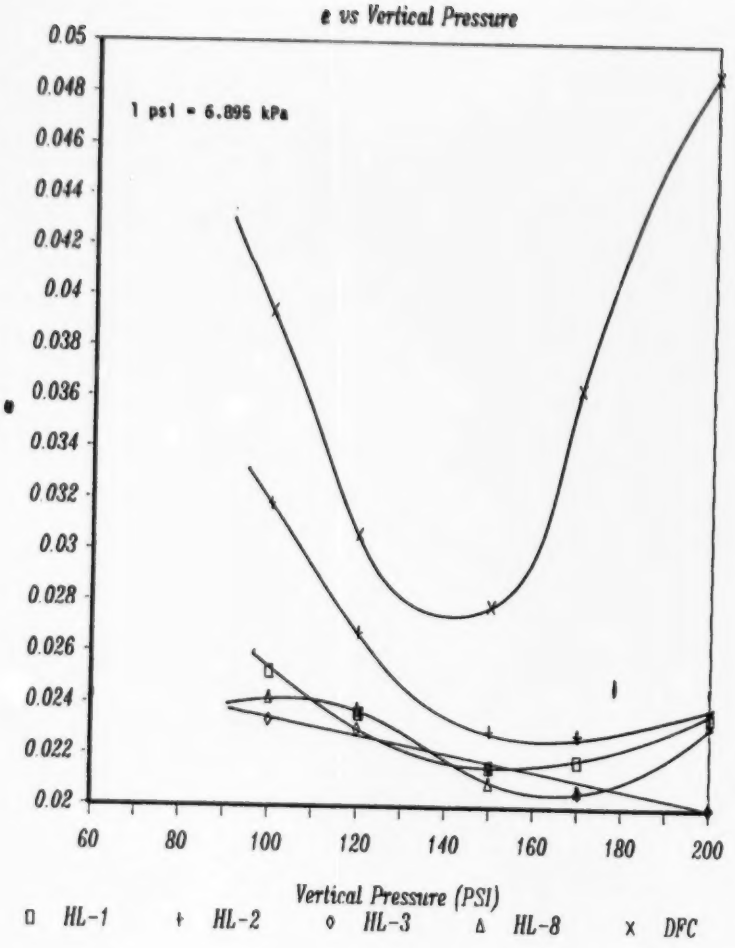

e vs Vertical Pressure
1 psi = 6.895 kPa
0.05
0.048
0.046
0.044
0.042
0.04
0.038
0.036
0.034
0.032
0.03
0.028
0.026
0.024
0.022
0.02
60
80
100
120
140
160
180
200
Vertical Pressure (PSI)
HL-1
HL-2
HL-3
HL-8
DFC

FIG. 10

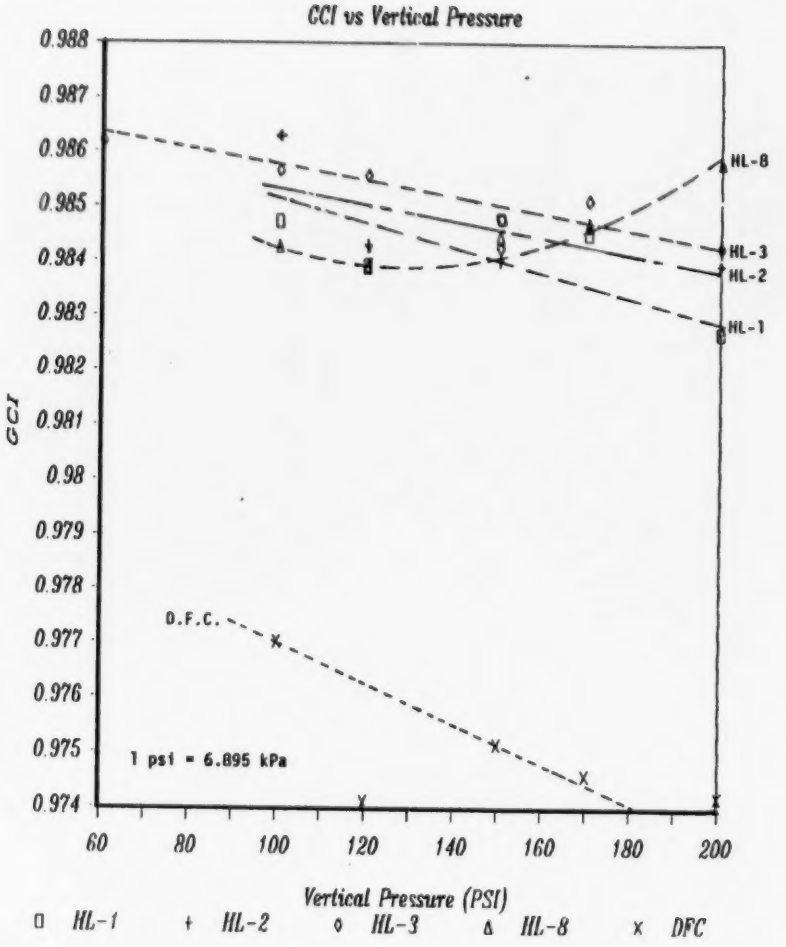

GCI vs Vertical Pressure
0.988
0.987
0.986
0.985
0.984
0.983
0.982
0.981
0.98
0.979
0.978
0.977
0.976
0.975
0.974
GCI
HL-8
HL-3
HL-2
HL-1
D.F.C.
1 psi = 6.895 kPa
60
80
100
120
140
160
180
200
Vertical Pressure (PSI)
HL-1
HL-2
HL-3
HL-8
DFC

FIG. 11

FIG. 12

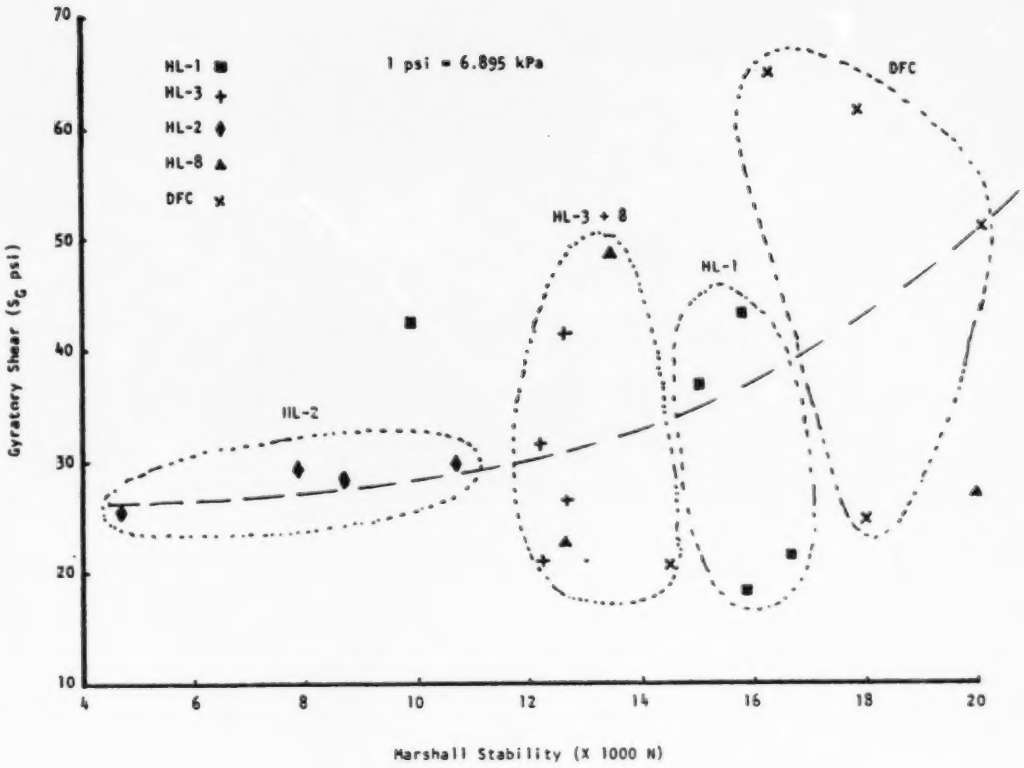

HL-1
HL-3
HL-2
HL-8
DFC
1 psi = 6.895 kPa
HL-3 + 8
HL-1
DFC
HL-2
Gyratory Shear (S_G psi)
Marshall Stability (X 1000 N)
70
60
50
40
30
20
10
4
6
8
10
12
14
16
18
20

FIG. 13

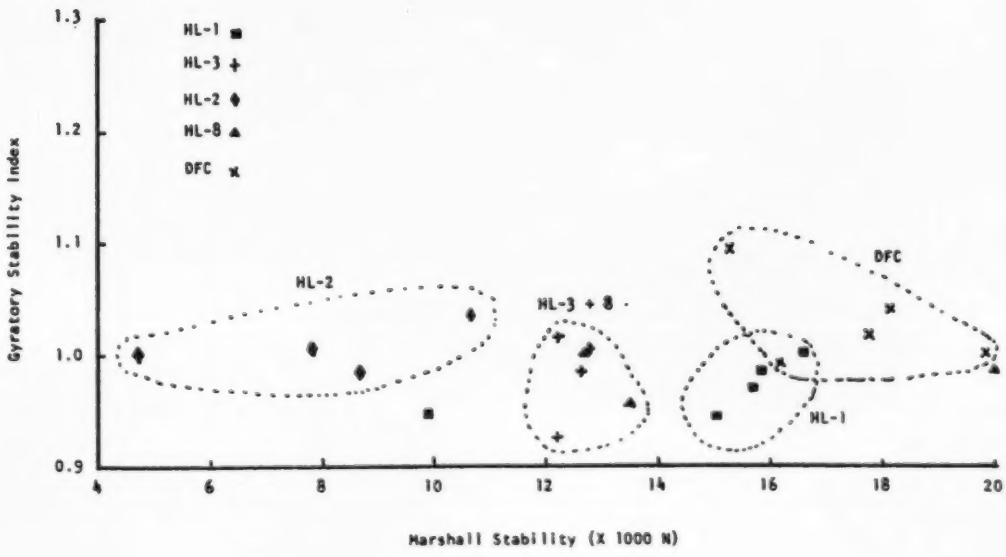

HL-1
HL-3
HL-2
HL-8
DFC
HL-2
HL-3 + 8
DFC
HL-1
Gyratory Stability Index
Marshall Stability (X 1000 N)
1.3
1.2
1.1
1.0
0.9
4
6
8
10
12
14
16
18
20

Fig. 14: Rutting on Hwy. 401 Eastbound

Fig. 15: Bloomington Road, Regional Municipality of York

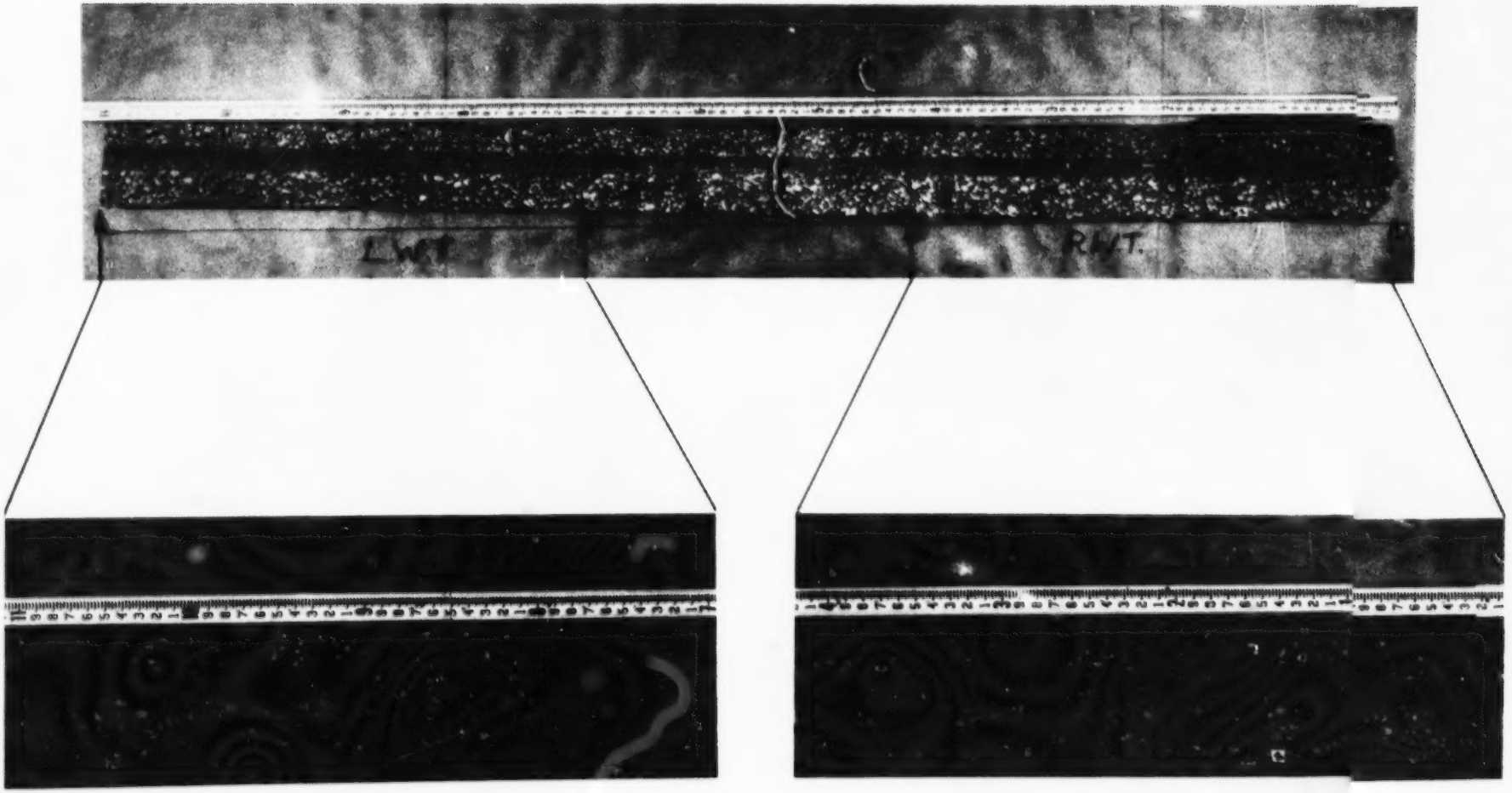


Fig. 16: Layer Thickness of Pavement Section, Hwy. 401, Port Hope

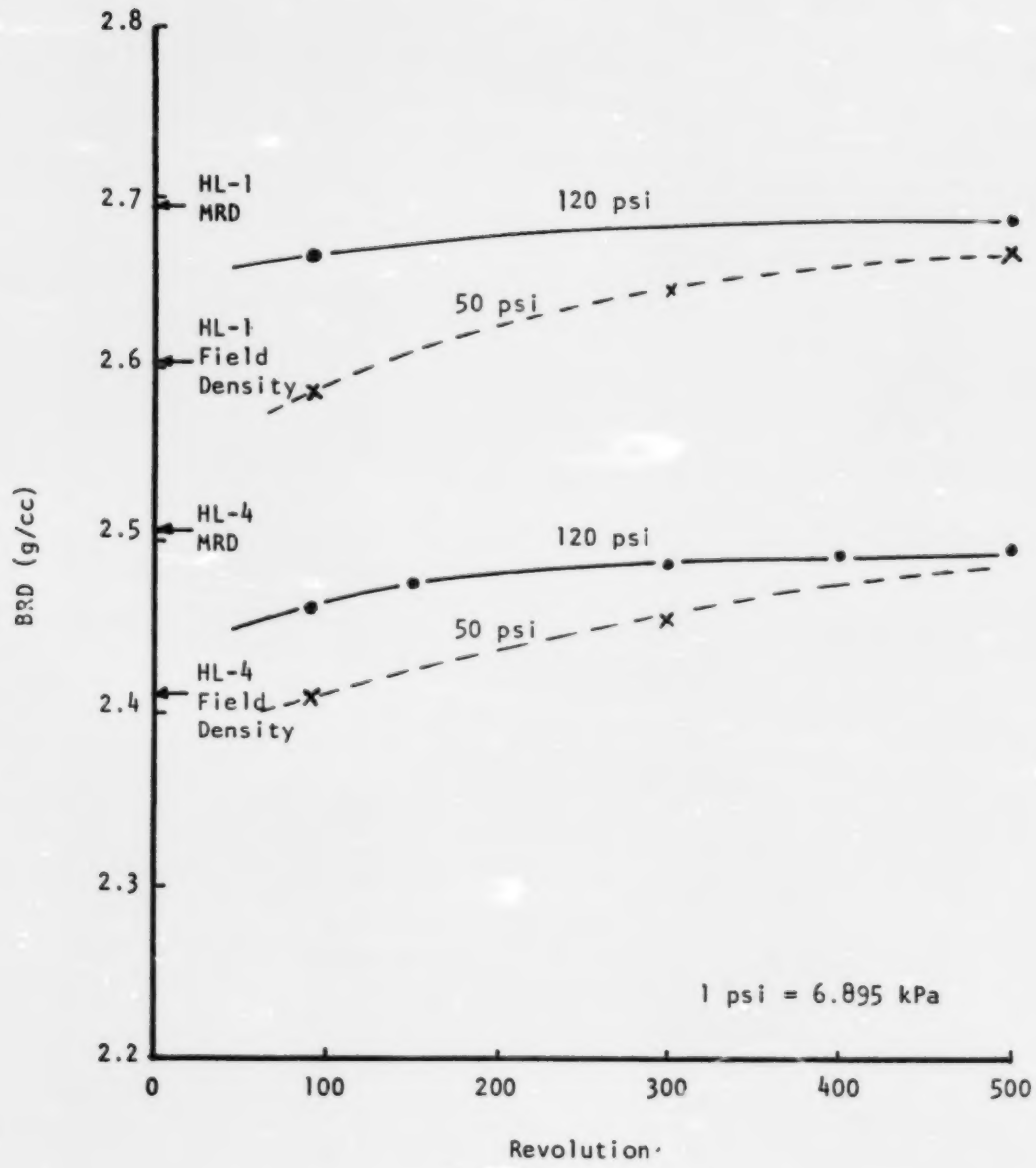

2.8
2.7
2.6
2.5
2.4
2.3
2.2
BRD (g/cc)
HL-1
MRD
120 psi
50 psi
HL-1
Field
Density
HL-4
MRD
120 psi
50 psi
HL-4
Field
Density
1 psi = 6.895 kPa
0
100
200
300
400
500
Revolution

FIG. 17

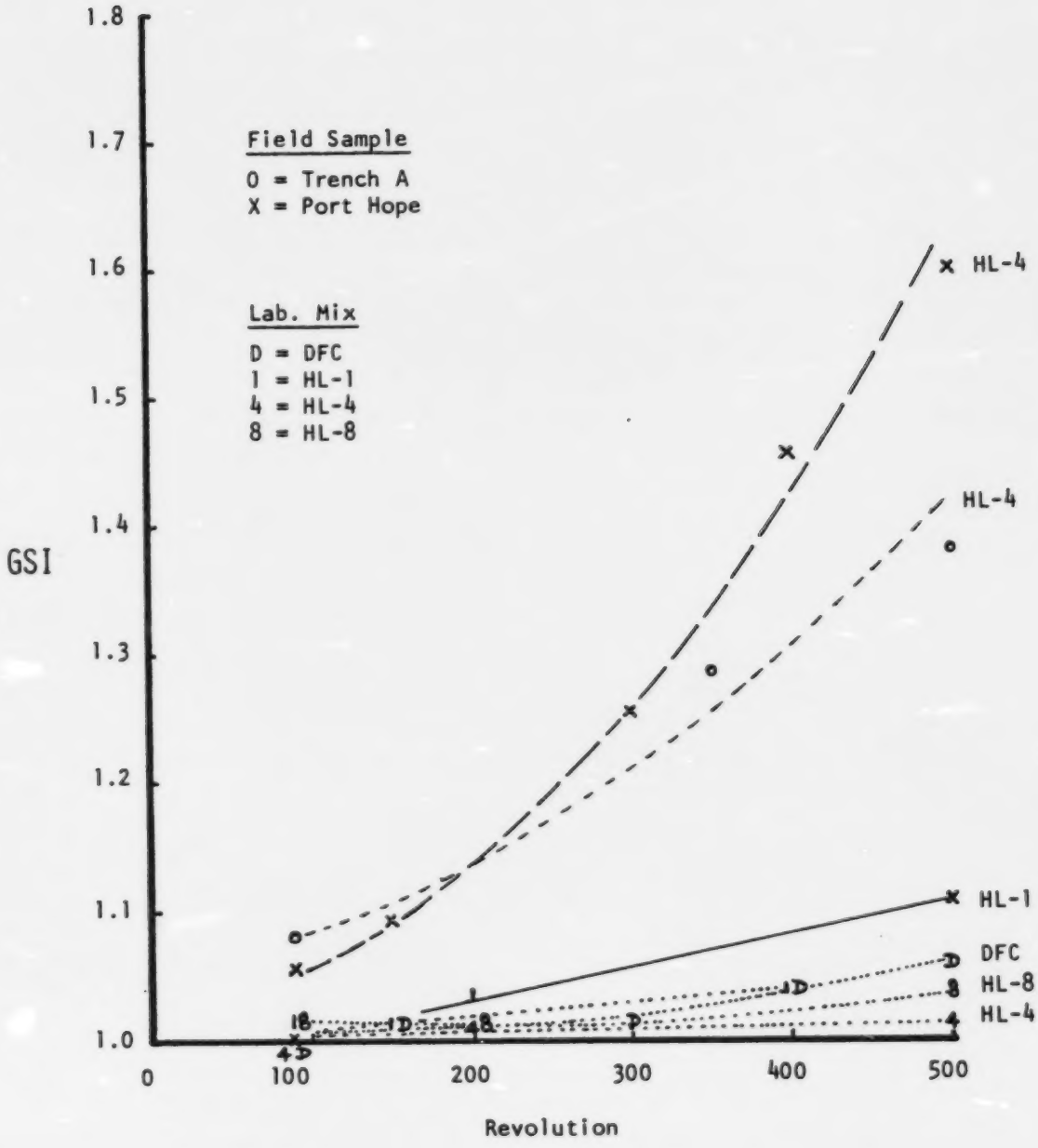


FIG. 18: GYRATORY STABILITY INDEX (GSI) VS. REVOLUTION AT 827 kPa VERTICAL PRESSURE

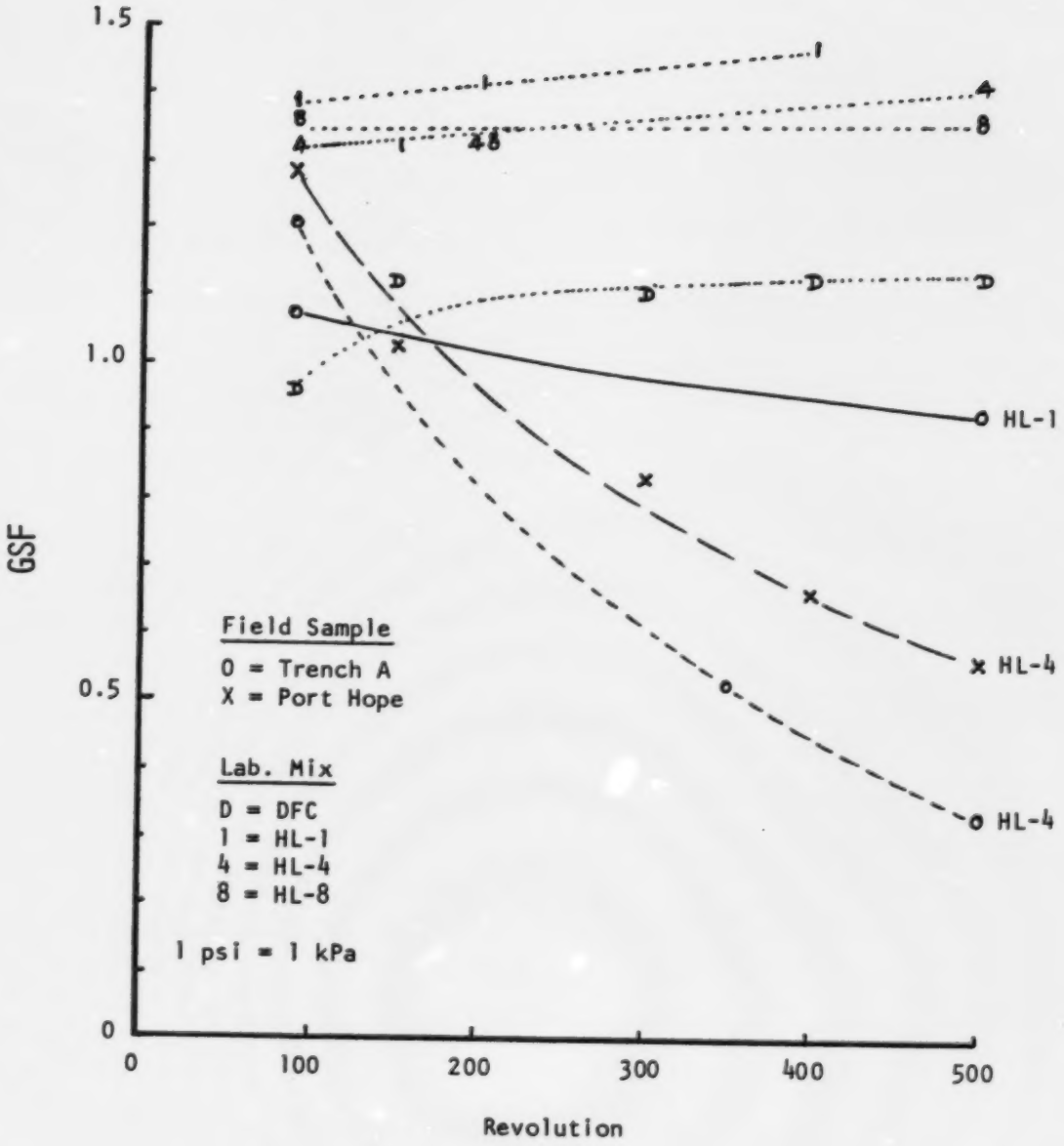

1.5
1.0
0.5
0
GSF
0
100
200
300
400
500
Revolution
HL-1
HL-4
HL-4
Field Sample
0 = Trench A
X = Port Hope
Lab. Mix
D = DFC
1 = HL-1
4 = HL-4
8 = HL-8
1 psi = 1 kPa

FIG. 19

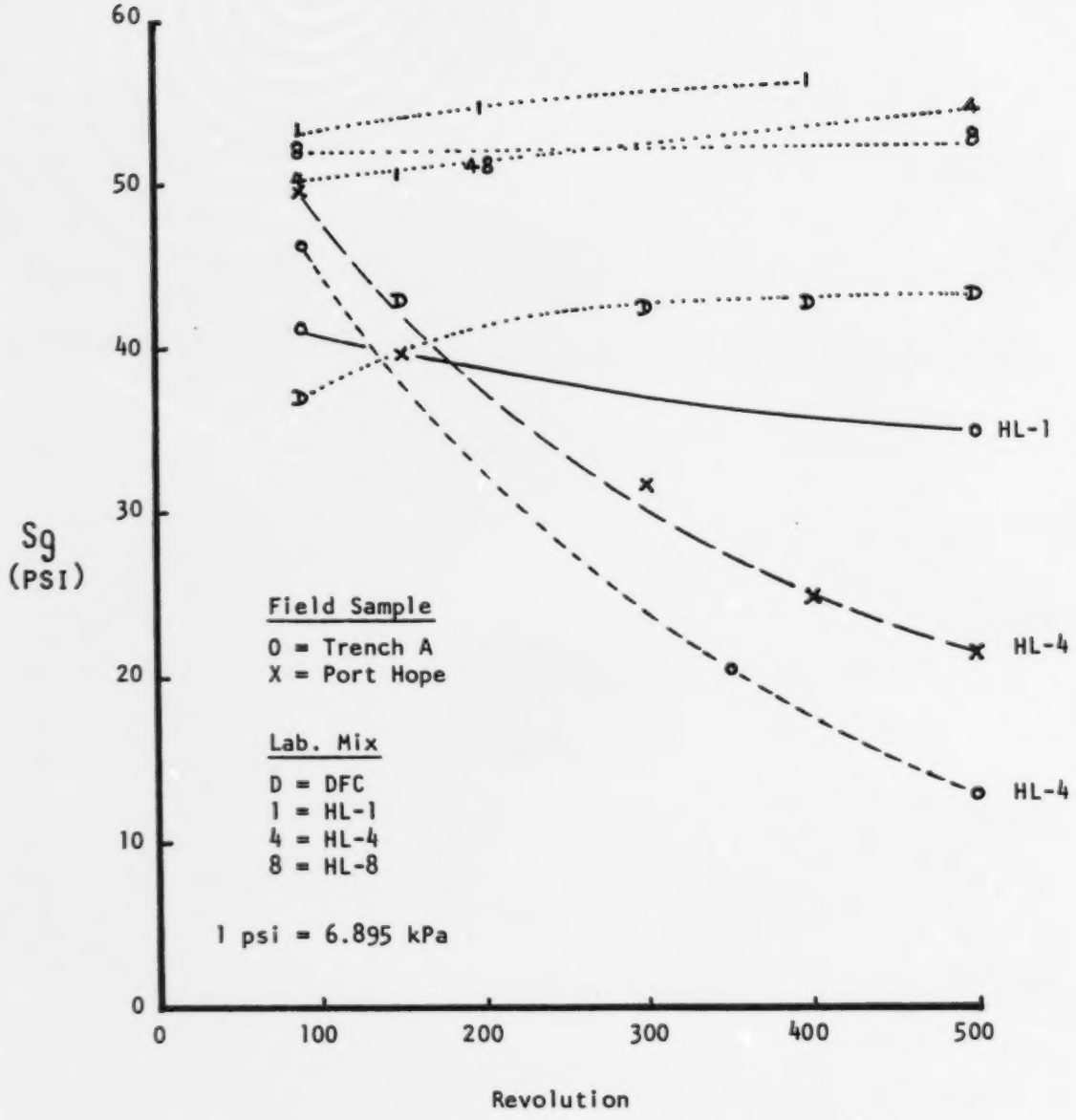


FIG. 20: GYRATORY SHEAR VS. REVOLUTION AT 827 KPA VERTICAL PRESSURE

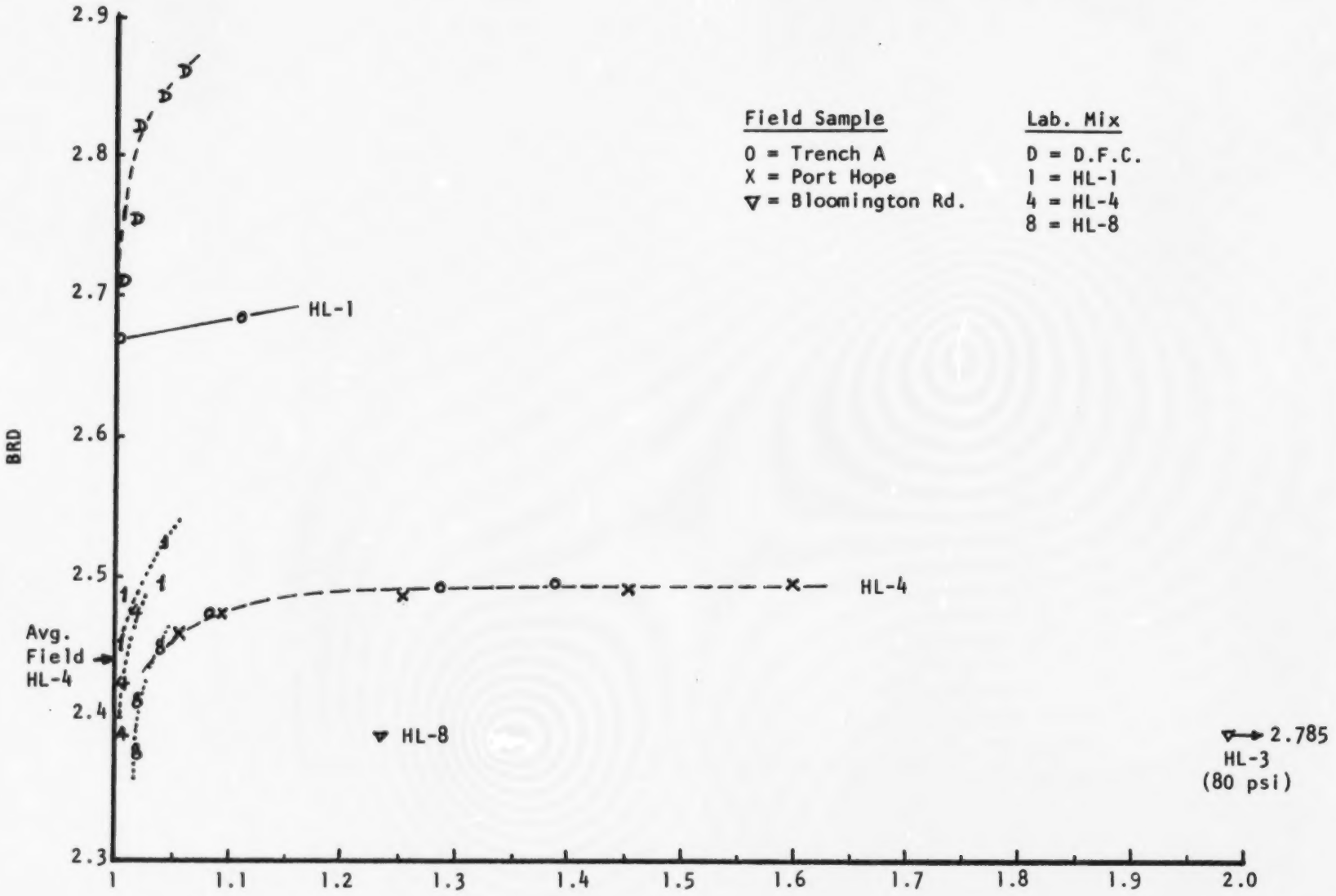

Field Sample
0 = Trench A
X = Port Hope
▽ = Bloomington Rd.
Lab. Mix
D = D.F.C.
1 = HL-1
4 = HL-4
8 = HL-8
HL-1
HL-4
HL-8
Avg. Field HL-4
▽ 2.785
HL-3
(80 psi)
BRD
2.9
2.8
2.7
2.6
2.5
2.4
2.3
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
Gyratory Stability Index (GSI)

Fig. 2

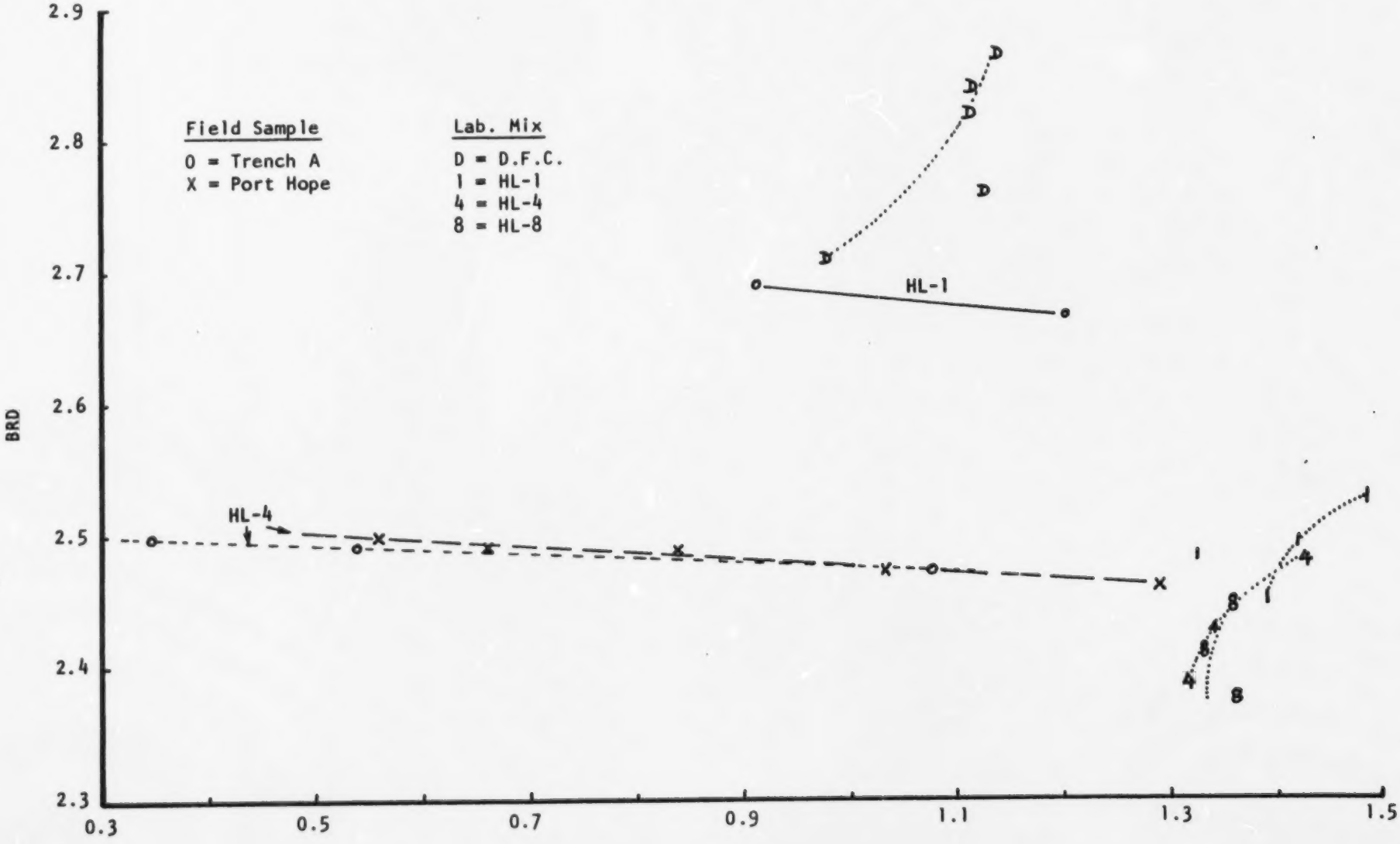
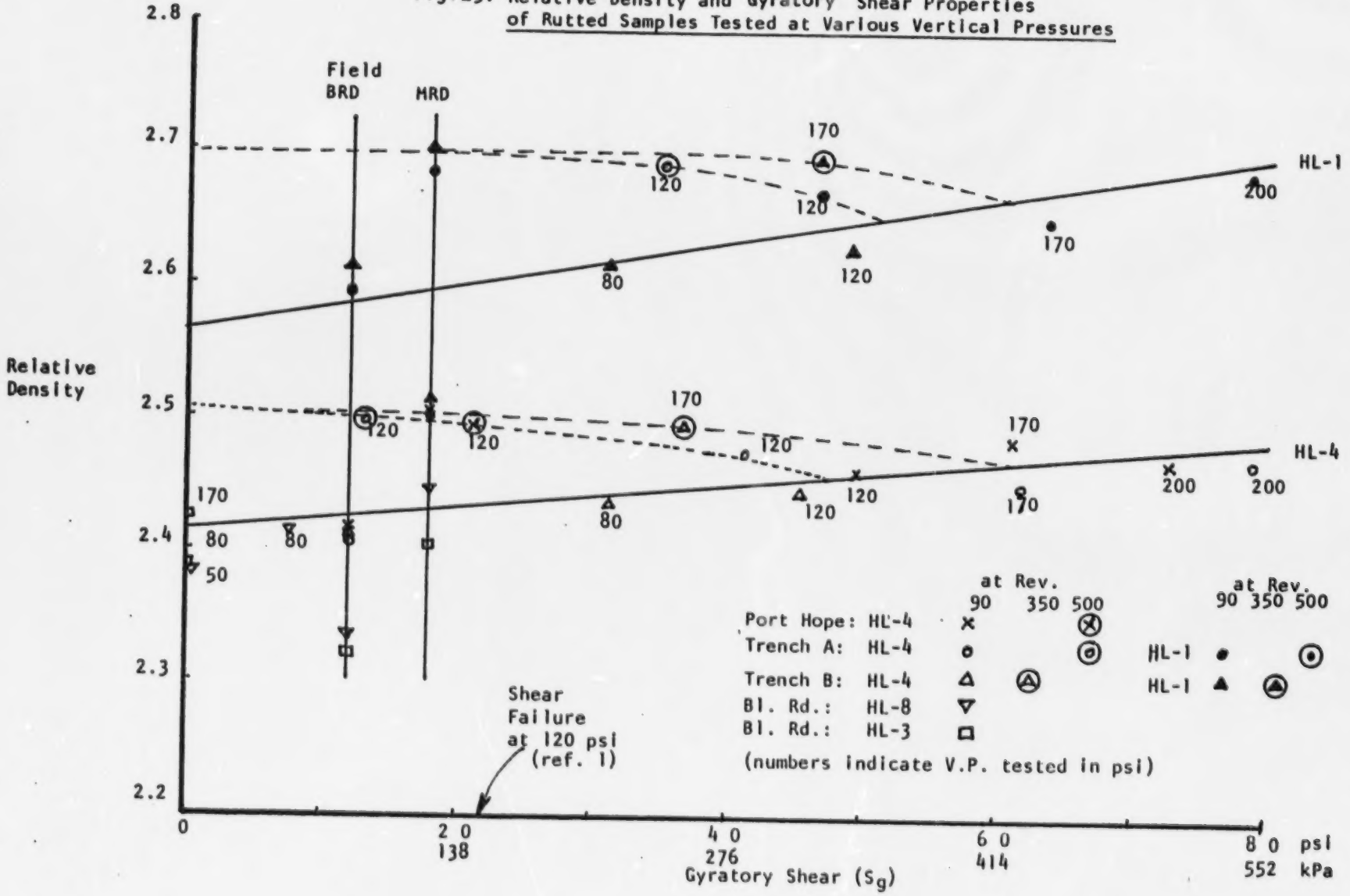

Field Sample
0 = Trench A
X = Port Hope
Lab. Mix
D = D.F.C.
1 = HL-1
4 = HL-4
8 = HL-8
HL-1
HL-4
BRD
GSF
2.9
2.8
2.7
2.6
2.5
2.4
2.3
0.3
0.5
0.7
0.9
1.1
1.3
1.5

Fig. 22

Fig.23: Relative Density and Gyratory Shear Properties of Rutted Samples Tested at Various Vertical Pressures



SIEVE DESIGNATION	PERCENTAGE PASSING BY DRY MASS			
	HL 1 and 3	HL 2	HL 4	HL 8
26.5 mm				100
19.0 mm			100	94 - 100
16.0 mm	100		98 - 100	77 - 95
13.2 mm	98 - 100		83 - 95	
9.5 mm	75 - 90	100	62 - 82	48 - 78
4.75mm	45 - 65	85 - 100	40 - 67	30 - 55
2.36mm	36 - 64	70 - 90	27 - 66	21 - 54
1.18mm	25 - 58	50 - 75	16 - 60	12 - 49
600um	16 - 45	30 - 55	8 - 47	6 - 38
300um	7 - 26	15 - 35	4 - 27	3 - 22
150um	3 - 10	5 - 16	1 - 10	1 - 9
75um	0 - 5	3 - 8	0 - 6	0 - 6

Table 1: Gradation Requirements for Evaluated Mixtures

TABLE 2

MARSHALL MIX DESIGN DATA

CONTRACT	MIX TYPE	C/A	F/A 1	F/A 2	DESIGN AC%	MIX BRD (g/cc)	MARSHALL STABILITY (N)	FLOW (.25mm)	% AIR VOIDS	%VMA	% Ret. 4.75 mm
84-56	HL-1	CSS	SNS-W		4.7	2.72	16600	10	3	14.2	50
85-526	HL-1	CSS	SNS	SNS-W	5.1	2.64	15900	10	3	15	45
85-19	HL-1	CSS	FS	RS	5.3	2.62	15100	10.6	2.8	14.4	50
85-50	HL-1	CR	MS		5	2.53	9900	9.9	3	15.3	50
85-49	HL-1	CSS	FS	MS	5.3	2.73	15700	10	2.8	14.7	50

G.T.M. PROPERTIES

CONTRACT	VERT PRESS (psi)	Sg (psi)	ε (in/in)	Eg (psi)	GSF	GSI	ROLLER PRESS (psi)	MIX BRD (g/cc)	GCI
84-56	120	41.44	0.0244	4922	1.082	1.011	26.86	2.74	0.9821
	150	59.60	0.0206	7271	1.248	1.019	37.16	2.73	0.9844
	170	62.55	0.0228	7463	1.155	1.015	38.80	2.75	0.9840
	200	73.83	0.0225	8881	1.168	1.015	45.17	2.76	0.9848
85-526	100	29.42	0.0270	3701	0.924	0.988	22.40	2.66	0.9851
	120	40.50	0.0232	5177	1.058	0.992	29.00	2.63	0.9852
	150	51.73	0.0226	6628	1.083	0.988	37.00	2.66	0.9848
	170	61.02	0.0205	8281	1.159	0.989	42.96	2.66	0.9848
85-19	100	27.90	0.0294	3406	0.877	1.011	19.20	2.61	0.9845
	120	36.88	0.0260	4621	0.964	0.942	24.00	2.62	0.9847
	150	50.45	0.0234	6405	1.056	0.992	33.00	2.63	0.9852
	170	59.46	0.0209	8146	1.131	0.974	38.40	2.64	0.9854
85-50	100	42.70	0.0193	5173	1.341	0.946	30.66	2.53	0.9846
	120	43.07	0.0221	5423	1.125	0.981	31.00	2.54	0.9839
	150	64.17	0.0189	7924	1.343	0.981	44.33	2.55	0.9852
	170	71.39	0.0193	8827	1.308	0.998	48.94	2.55	0.9853
85-49	120	43.73	0.0220	5462	1.142	0.975	29.86	2.73	0.9835
	150	59.29	0.0199	7523	1.241	0.966	39.93	2.73	0.9835
	170	61.25	0.0232	7340	1.132	1.015	41.20	2.73	0.9831
	200	70.49	0.0246	8140	1.099	1.047	47.18	2.73	0.9801
AVERAGE	100	33.34	0.0252	3964	1.047	0.982	24.08	2.60	0.9847
	120	41.13	0.0235	5102	1.074	0.980	28.14	2.65	0.9839
	150	57.05	0.0211	7106	1.194	0.989	38.28	2.66	0.9846
	170	63.13	0.0213	7974	1.177	0.998	42.06	2.67	0.9845
	200	72.16	0.0235	8496	1.134	1.031	46.18	2.75	0.9825

(1 psi = 6.895 kPa; 1 lbf = 4.448 N; 1 lb/ft^3 = 1.603×10^{-2} g/cc; 1 in = 25.4 mm)

TABLE 3

MARSHALL MIX DESIGN DATA

CONTRACT	MIX TYPE	C/A	F/A 1	F/A 2	DESIGN AC%	MIX BRD (g/cc)	MARSHALL STABILITY (N)	FLOW (.25mm)	% AIR VOIDS	%VMA	% Ret. 4.75 mm
84-94	HL-2		SNS	SNS	7.1	2.32	8700	10.7	3.2	19.6	3.7
84-95	HL-2		SNS-W	RS	6.5	2.38	10700	9.2	3.2	17.8	9.5
84-45	HL-2		SNS-W		8	2.28	4700	9	4.4	21.7	8.9
84-33	HL-2		SNS	RS	6.8	2.38	7800	9.6	3	17.1	12.3

G.T.M. PROPERTIES

CONTRACT	VERT PRESS (psi)	Sg (psi)	ε (in/in)	Eg (psi)	GSF	GSI	ROLLER PRESS (psi)	MIX BRD (g/cc)	GCI
84-94	100	28.59	0.0297	3366	0.898	0.983	24.00	2.32	0.9844
	120	32.96	0.0306	3919	0.861	1.000	27.33	2.33	0.9848
	150	46.86	0.0261	5741	0.982	0.994	37.33	2.34	0.9852
	170	53.68	0.0251	6776	1.003	1.001	42.33	2.35	0.9856
84-95	120	42.01	0.0240	4994	1.097	1.038	32.00	2.42	0.9819
	150	48.07	0.0238	6297	1.006	1.020	36.00	2.42	0.9818
	170	50.66	0.0282	6022	0.936	1.038	38.66	2.44	0.9840
	200	55.63	0.0314	6363	0.839	1.043	42.66	2.45	0.9856
84-45	100	25.95	0.0318	3143	0.815	1.000	23.00	2.25	0.9863
	120	34.52	0.0287	4181	0.902	1.000	29.00	2.26	0.9864
	150	51.77	0.0235	6391	1.084	1.000	38.66	2.27	0.9862
	170	61.81	0.0202	8433	1.188	1.000	44.88	2.27	0.9862
84-33	120	45.78	0.0209	5755	1.196	0.992	34.33	2.39	0.9840
	150	62.31	0.0186	8086	1.305	0.969	45.00	2.40	0.9830
	170	72.27	0.0180	9434	1.335	0.984	51.46	2.40	0.9829
	200	88.00	0.0165	12136	1.413	0.984	61.64	2.41	0.9824
AVERAGE	100	25.95	0.0318	3143	0.815	1.000	23.00	2.25	0.9863
	120	36.77	0.0268	4481	0.991	1.003	29.33	2.35	0.9843
	150	52.25	0.0230	6525	1.094	0.996	39.25	2.36	0.9840
	170	59.60	0.0229	7433	1.116	1.006	44.33	2.37	0.9847
	200	71.82	0.0240	8351	1.126	1.013	52.15	2.43	0.9840

(1 psi = 6.895 kPa; 1 lbf = 4.448 N; 1 lb/ft^3 = 1.603×10^{-2} g/cc; 1 in = 25.4 mm)

TABLE 4

MARSHALL MIX DESIGN DATA

CONTRACT	MIX TYPE	C/A	F/A 1	F/A 2	DESIGN AC%	MIX BRD (g/cc)	MARSHALL STABILITY (N)	FLOW (.25mm)	% AIR VOIDS	%VMA	% Ret. 4.75 mm
83-11	HL-3	CR	SNS	SNS-W	5.6	2.39	12200	8.4	1.8	14.8	30
83-11	HL-3	CR	SNS	SNS-W	5.6	2.39	12200	8.4	1.8	14.8	30
84-33	HL-3	CR	SNS		5.7	2.42	12600	9.3	2	14.6	30
84-85	HL-3	CR	SNS		5.6	2.35	12700	9	4.3	15.8	45

G.T.M. PROPERTIES

CONTRACT	VERT PRESS (psi)	Sg (psi)	e (in/in)	Eg (psi)	GSF	GSI	ROLLER PRESS (psi)	MIX BRD (g/cc)	GCI
83-11	59.5	21.13	0.0243	2449	1.115	1.017	16.86	2.42	0.9862
	100	37.12	0.0234	4279	1.166	1.017	28.26	2.44	0.9857
	150	59.92	0.0206	7299	1.255	1.005	42.86	2.45	0.9861
	170	68.43	0.0198	8603	1.285	1.002	48.60	2.46	0.9861
83-11	120	45.73	0.0218	5512	1.194	0.962	34.20	2.40	0.9864
	150	58.25	0.0207	7243	1.219	1.000	42.86	2.47	0.9869
	170	67.73	0.0205	8313	1.251	1.000	48.53	2.42	0.9872
	200	81.10	0.0197	10137	1.288	1.019	57.11	2.42	0.9877
84-33	120	43.76	0.0219	5484	1.143	0.985	31.86	2.42	0.9846
	150	56.04	0.0208	7225	1.173	0.976	40.33	2.43	0.9853
	170	64.87	0.0202	8399	1.198	0.961	45.79	2.43	0.9860
	200	77.64	0.0193	10368	1.232	0.946	54.13	2.43	0.9869
84-85	120	38.73	0.0245	4908	1.012	1.020	29.26	2.38	0.9890
	150	50.02	0.0232	6474	1.047	1.008	36.53	2.39	0.9824
	170	63.42	0.0216	7889	1.171	1.011	44.00	2.40	0.9823
	200	79.11	0.0197	10152	1.282	1.008	53.23	2.41	0.9789
AVERAGE	59.5	21.13	0.0243	2449	1.115	1.017	16.86	2.42	0.9862
	100	37.12	0.0234	4279	1.166	1.017	28.26	2.44	0.9857
	120	42.74	0.0227	5286	1.116	0.989	31.77	2.40	0.9867
	150	54.77	0.0215	6964	1.147	0.995	39.91	2.43	0.9849
	170	64.88	0.0205	8289	1.232	0.996	45.96	2.43	0.9856
	200	79.28	0.0196	10220	1.267	0.991	54.82	2.42	0.9845

(1 psi = 6.895 kPa; 1 lbf = 4.448 N; 1 lb/ft^3 = 1.603×10^{-2} g/cc; 1 in = 25.4 mm)

TABLE 5

MARSHALL MIX DESIGN DATA

CONTRACT	MIX TYPE	C/A	F/A 1	F/A 2	DESIGN AC%	MIX BRD (g/cc)	MARSHALL STABILITY (N)	FLOW (.25mm)	% AIR VOIDS	%VMA	% Ret. 4.75 mm
85-19	HL-8	CR	FS	RS	5.3	2.35	12100	10.2	3.2	14.3	45
85-49	HL-8	CR	FS	MS	5.1	2.43	20500	16.4	3	13.9	45
84-85	HL-8	CR	SNS-W		5.2	2.41	12700	9.5	2.9	14.3	45
84-85	HL-8	CR	SNS		5.5	2.38	13450	9.9	3.8	14.8	45

G.T.M. PROPERTIES

CONTRACT	VERT PRESS (psi)	Sg (psi)	e (in/in)	Eq (psi)	GSF	GSI	ROLLER PRESS (psi)	MIX BRD (g/cc)	GCI
85-19	100	27.70	0.0298	3355	0.870	1.000	22.66	2.41	0.9841
	120	34.02	0.0291	4121	0.889	1.019	27.66	2.42	0.9853
	150	49.96	0.0248	6051	1.046	1.000	38.00	2.44	0.9845
	170	58.43	0.0230	7391	1.108	1.003	43.95	2.44	0.9848
85-49	120	39.19	0.0249	4825	1.025	0.992	31.06	2.44	0.9833
	150	57.62	0.0209	7184	1.207	1.003	43.86	2.46	0.9841
	170	59.78	0.0235	7249	1.104	0.976	46.13	2.46	0.9849
	200	70.61	0.0234	8551	1.118	0.962	54.23	2.47	0.9858
84-85	100	32.83	0.0258	3874	1.031	1.038	24.66	2.43	0.9854
	120	42.85	0.0223	5386	1.119	1.000	31.00	2.44	0.9847
	150	62.67	0.0189	7937	1.313	1.016	44.39	2.44	0.9854
	170	74.29	0.0160	10618	1.421	1.003	52.03	2.44	0.9853
84-85	100	50.04	0.0172	5821	1.572	0.979	36.50	2.39	0.9833
	120	51.47	0.0190	6306	1.345	1.000	38.00	2.39	0.9823
	150	63.37	0.0192	7825	1.327	0.985	45.00	2.42	0.9839
	170	68.05	0.0201	8441	1.208	0.990	48.08	2.44	0.9839
AVERAGE	100	36.86	0.0243	4122	1.158	1.005	27.94	2.41	0.9843
	120	41.88	0.0238	5038	1.095	1.003	31.93	2.42	0.9839
	150	58.41	0.0209	7167	1.223	1.001	42.81	2.44	0.9845
	170	65.14	0.0207	8232	1.210	0.993	47.55	2.45	0.9847
	200	70.61	0.0234	8551	1.118	0.962	54.23	2.47	0.9858

(1 psi = 6.895 kPa; 1 lbf = 4.448 N; 1 lb/ft^3 = 1.603×10^{-2} g/cc; 1 in = 25.4 mm)

TABLE 6

MARSHALL MIX DESIGN DATA

CONTRACT	MIX TYPE	C/A	F/A 1	F/A 2	DESIGN AC%	MIX BRD (g/cc)	MARSHALL STABILITY (N)	FLOW (.25mm)	% AIR VOIDS	%VMA	% Ret. 4.75 mm
84-56	DFC	CSS	SSS		5.2	2.99	18100	18.7	2.5	13.6	45
85-19	DFC	CSS	SSS		5.5	2.97	14700	17	1.7	11.3	55
84-45	DFC	CSS	SSS		5.1	2.98	19900	17.6	2.5	13.7	55
84-01	DFC	CSS	SSS		5.6	2.93	17800	13.8	3.2	12.1	45
84-87	DFC	CSS	SSS		5.6	2.97	16200	14.9	1.6	13.5	45

G.T.M. PROPERTIES

CONTRACT	VERT PRESS (psi)	Sg (psi)	ε (in/in)	Eg (psi)	GSF	GSI	ROLLER PRESS (psi)	MIX BRD (g/cc)	GCI
84-56	120	33.40	0.0302	3971	0.873	1.008	24.46	2.96	0.9760
	150	42.48	0.0296	5071	0.890	1.004	30.60	2.98	0.9759
	170	25.51	0.0689	2469	0.472	1.043	17.80	2.98	0.9791
	200	17.33	0.0980	2041	0.166	1.071	11.26	3.00	0.9814
85-19	100	20.13	0.0449	2228	0.633	1.094	15.00	2.98	0.9782
	120	31.62	0.0331	3624	0.826	1.000	22.00	3.02	0.9734
	150	41.31	0.0317	4735	0.865	1.000	28.33	3.02	0.9730
	170	50.29	0.0253	6717	0.975	0.953	33.94	3.03	0.9705
84-45	100	23.60	0.0339	2950	0.741	0.970	17.86	2.96	0.9759
	120	29.68	0.0340	3527	0.776	1.011	21.00	2.99	0.9756
	150	43.81	0.0284	5280	0.918	0.996	29.40	2.97	0.9768
	170	51.56	0.0266	6391	0.982	1.011	33.77	2.98	0.9771
84-01	120	37.85	0.0254	4726	0.989	0.988	28.46	2.88	0.9727
	150	54.11	0.0225	6673	1.133	0.989	37.93	2.90	0.9772
	170	56.45	0.0248	6863	1.043	1.004	40.13	2.91	0.9718
	200	66.34	0.0250	7987	1.048	1.016	46.52	2.93	0.9699
84-87	120	33.33	0.0304	3951	0.871	0.985	24.20	2.93	0.9728
	150	47.16	0.0271	5539	0.988	0.989	32.80	2.95	0.9729
	176	55.71	0.0254	6921	1.029	0.989	38.40	2.96	0.9718
	200	65.19	0.0234	8565	1.096	0.990	44.42	2.97	0.9713
AVREAGE	100	21.86	0.0394	2539	0.687	1.032	16.43	2.97	0.9770
	120	33.18	0.0306	3919	0.867	0.998	24.02	2.96	0.9741
	150	45.78	0.0278	5388	0.959	0.996	31.81	2.96	0.9752
	170	45.95	0.0364	4673	0.868	1.003	31.41	2.98	0.9746
	176	55.71	0.0254	6921	1.029	0.989	38.40	2.96	0.9718
	200	49.62	0.0488	4099	0.770	1.026	34.07	2.97	0.9742

(1 psi = 6.895 kPa; 1 lbf = 4.448 N; 1 lb/ft^3 = 1.603 x 10^{-2} g/cc; 1 in = 25.4 mm)

Mix	Agg. Type		% A.C.	C.A. / F.A.	% Voids	% VMA	Stability (N)	Flow (0.25mm)	BRD	MRD
	Coarse (C.A.)	Fine (F.A.)								
HL-1	3M (traprock)	Durham (limestone gravel)	5.1	46/54	4.0	14.9	16555	9.3	2.521	2.626
HL-4	Durham (limestone gravel)	Durham (limestone gravel)	5.3	46/54	3.7	14.6	16600	9.2	2.435	2.529
HL-8	Taro (crushed limestone)	Oak Park (natural sand)	5.3	46/54	4.0	15.7	10278	7.9	2.408	2.508
DFC	Steetley (steel slag)	Steetley (steel slag)	5.6	40/60	1.5	13.5	16200	14.9	3.015	3.061

TABLE 7 Property of Different Laboratory Mixes

TABLE 8: FIELD SAMPLE PROPERTIES

Mix Type	% A.C.	Marshall Recompaction			Pavement Sample			% Retained Cumulative										
								mm							μm			
		% Voids	Flow	Stab.	% Voids	% Comp.	Lift	16.0	13.2	9.5	6.7	4.75	2.36	1.18	600	300	150	75
Hwy. 401, Port Hope																		
HL-4	4.70	2.5	12.2	11,530	3.9	98.5	B		5	23	35	43	54	64	73	84	95	97.3
Hwy. 401, Trench 'A'																		
HL-1	4.93	2.6	13.8	18,450	3.4	99.2	S			15	34	46	58	67	79	89	96	97.6
HL-4	5.30	2.7	13.3	14,370	3.7	99.0	B	1	4	20	31	39	50	61	73	85	95	97.4
Hwy. 401, Trench 'B'																		
HL-1	5.19	2.4	14.2	16,960	3.3	99.2	S			14	33	46	57	63	69	84	94	96.4
HL-4	5.22	3.1	11.8	12,490	4.2	98.9	B	1	4	20	34	42	51	58	65	82	93	95.7
Bloomington Road																		
HL-3	8.2	1.5	25+	5,576	3.3	98.2	S			11	26	34	46	57	70	84	92	95.9
HL-8	6.6	1.7	25+	8,220	4.4	97.3	B	8	14	25	36	43	53	62	74	89	96	97.8

B = Binder Course
S = Surface Course

Table 9: RELATIVE DENSITY AND GYRATORY SHEAR RESULTS

(1 psi = 6.895 kPa)

SITE	MIX	Relative Density		MRD	% Field to MRD	AT 90 REV.			AT 300 OR 500 REV.			
		Field	Recomp.			GTM Bulk Density	Gyratory Shear (SG) (psi)	Vert Press. (psi)	GTM Bulk Density	Gyratory Shear (SG) (psi)		Vert. Press. (psi)
										300	500	
Hwy. 401 Port Hope	4	2.418	2.445	2.506	96.5	2.420 2.460 2.485 2.468	21.9 49.6 61.3 72.6	50 120 170 200	2.463 2.494	24.4 -	- 21.6	50 120
Hwy. 401 Trench A	1	2.596	2.618	2.686	96.6	2.586 2.665 2.648 2.682	18.6 46.1 63.9 78.2	50 120 170 200	2.689 2.673 2.646	- - 24.5	34.9 29.0 -	120 50 50
	4	2.412	2.436	2.502	96.4	2.415 2.478 2.451 2.470	21.0 41.2 61.6 78.4	50 120 170 200	2.458 2.497	23.5* -	- 12.8	50 120
Hwy. 401 Trench B	1	2.614	2.634	2.702	96.7	2.615 2.625	31.6 48.2	80 120	2.682	46.4*	-	170
	4	2.413	2.442	2.519	95.8	2.436 2.443	31.0 45.5	80 120	2.489	36.3*	-	170
Bloom-ington Road	3	2.320	2.364	2.400	96.7	2.387 2.424	0 0	80 170				
	8	2.336	2.403	2.443	95.6	2.388 2.417	0 7.7	50 80				

* Measured at 350 rev.

TABLE 10 GTM Results At Different Revolution of Compaction
(Tested at 827 kPa, 1 psi = 6.895 kPa)

	Mix	BRD	GSI	Sg (psi)	GSF	Rev.
Hwy. 401 Port Hope	4	2.460	1.054	49.6	1.294	90
	4	2.476	1.090	39.5	1.031	150
	4	2.487	1.254	31.9	0.835	300
	4	2.492	1.454	25.2	0.659	400
	4	2.494	1.600	21.6	0.564	500
Hwy. 401 Trench A	1	2.665	1.000	46.1	1.203	90
	1	2.689	1.113	34.9	0.912	500
	4	2.478	1.078	41.2	1.075	90
	4	2.491	1.288	20.4	0.533	350
	4	2.497	1.384	12.8	0.336	500
Hwy. 401 Trench B	1	2.625	1.007	48.2	1.258	90
	4	2.443	1.021	45.5	1.189	90
Bloomington Road	3*	2.387	2.785	0	0	90
	8**	2.388	1.152	0	0	90
	8	2.389	1.228	8.4	0.219	90
Lab Mix	1	2.456	1.018	53.5	1.396	90
	1	2.482	1.018	50.9	1.329	150
	1	2.495	1.037	54.3	1.419	200
	1	2.530	1.037	56.7	1.482	400
	4	2.389	1.000	50.4	1.317	90
	4	2.430	1.000	51.3	1.341	200
	4	2.480	1.018	54.6	1.425	500
	8	2.379	1.019	52.3	1.366	90
	8	2.415	1.019	51.0	1.333	200
	8	2.451	1.038	52.4	1.367	500
	DFC	2.711	1.000	37.2	0.972	90
	DFC	2.758	1.019	43.1	1.125	150
	DFC	2.821	1.019	42.2	1.102	300
	DFC	2.846	1.038	42.6	1.112	400
	DFC	2.866	1.057	43.4	1.133	500

*tested at 80 psi
**tested at 50 psi

TABLE 11 Degradation of Aggregates at Different Revolution of Compaction with the GTM

MIX	REV at 827 kPa V.P.	% Retained Cumulative										
		mm							um			
		16.0	13.2	9.5	6.7	4.75	2.36	1.18	600	300	150	75
HL-1	0			19	37	45	53	61	72	88	96	98.4
	90			18	36	45	52	60	70	85	93	96.1
	300			19	37	45	52	60	70	85	93	95.7
	500			18	37	46	53	61	71	85	93	96.2
HL-4	0		11	31	41	45	53	61	72	88	96	98.3
	90		10	29	39	44	51	59	70	85	93	95.7
	300		10	29	38	43	51	59	70	85	93	96.0
	500		10	31	39	44	52	60	70	84	92	95.3
HL-8	0	5	10	32	43	45	53	61	74	91	98	99.3
	90	4	9	30	41	44	52	60	72	88	95	97.2
	300	4	9	28	41	44	51	59	71	88	95	97.1
	500	4	10	29	40	44	51	60	71	89	95	97.4
DFC	0			20	35	47	71	84	90	93	96	97.2
	90			18	33	44	67	80	86	90	93	94.8
	300			21	33	44	67	80	86	90	92	94.7
	500			18	32	44	66	79	85	89	92	94.1
HL-4	90 Rev. at 1172 kPa V.P.	1	11	29	39	44	52	60	70	85	93	96.1
DFC	90 Rev. at 1172 kPa V.P.			18	33	44	66	79	86	90	93	94.7
Tolerances ± (Form 1150)		5	5	5	5	5	4	4	4	4	2	2

APPENDIX I

TYPE CODE

COARSE AGGREGATE

CR – Crushed Rock

CGS(x)(y) – Crushed–Gravel Stone (x) = % 1–Face (y) = % 2–Face

CBFS – Crushed Blast Furnace Slag

CSS – Crushed Steel Slag

GR – Gravel

FINE AGGREGATE

SNS – Screened Natural Sand

NS – Natural Sand

SCS – Scalped Sand

GS – Gravel Screenings

RS – Rock Screenings

MS – Manufactured Sand

FS – Foundry Sand

BLS – Blending Sand

BFSS – Blast Furnace Slag Screenings

SSS – Steel Slag Screenings

SUFFIXES

W – Washed

APPENDIX II - FORMULA

* Vertical Pressure on Specimen = $\frac{(\text{Ram Pressure} - 30)}{4.2}$

* Total Vertical Load = (Vertical Pressure X 12.566)

* Stability Index (GSI) $_{(30\ \text{rev})}$ = $\frac{\text{Max. Shear Strain (30 rev)}}{\text{Intermediate Shear Strain}}$

* Stability Index (GSI) $_{(60\ \text{rev})}$ = $\frac{\text{Max. Shear (60 rev)}}{\text{Inter. Shear Strain}}$

* Stability Index (GSI) $_{(90\ \text{rev})}$ = $\frac{\text{Max. Shear (90 rev)}}{\text{Inter. Shear Strain}}$

* Average Roller Pressure = $\frac{\Sigma\ \text{Roller Pressure}}{3}$ (For 30,60,90 rev)

* Average Specimen Height Reading = $\frac{\Sigma\ \text{Specimen Height Reading}}{3}$ (For 30,60,90 rev)

* Specimen Height = 2.5 + (Avg. Specimen Ht. Reading - Spacer Ht.) X 0.001

* Unit Mass $_{(CT)}$ = $\frac{\text{Total Batch Mass}}{\text{Spec. Height}}$ X 0.303 (For 30,60,90 rev)

* Compaction Index (GCI) = $\frac{\text{Unit Mass CT (30 rev)}}{\text{Unit Mass CT (60 rev)}}$

* Bitumen Mass = $\frac{\text{Bitumen Content X Total Batch Mass}}{100}$ (For 30,60,90 rev)

* Unit Mass $_{(RT)}$ =

$$\frac{\text{Total Batch Mass x 62.4}}{206.2 \times \text{Spec. Height} - \frac{\text{Bitumen Mass X 0.0004 X (Comp. Temp. - Room Temp.)}}{\text{Sp. Gr. Asphalt}}}$$

* Volume $_{(90\ \text{rev})}$ = Wt. of Sample in Air (Surface Dry) (90 rev) - Wt. of Sample in Water (90 rev)

* Specific Gravity $_{(90)}$ = $\frac{\text{Wt. of Sample in air}}{\text{Volume}}$

* Unit Mass $_{(TH)}$ = Sp. Grav. x 62.4

* Wall Friction = $\frac{\text{Wall Friction Reading on Gage} - 25)}{0.493}$ If WF <0 then WF = 0

* Calculated Gyratory Shear (S_G) =

$$\frac{50 \times \text{Roller Press.} - 2.55 \times \text{Wall Frict.} + \text{Tot.Ver.Load} \times \text{Spec. Ht.} \times 0.017455}{12.56 \times \text{Specimen Height}}$$

(For 30,60,90 rev)

* Gyratory Shear(S_G)= Calculated Gyratory Shear - 5 If S_G <5 then S_G = 0 (For 30,60,90 rev)

* Stress (τ max.) = $\frac{\text{Vertical Press on Specimen}}{\pi}$ (For 30,60,90 rev)

* Gyratory Shear Factor (GSF) = $\frac{\text{Gyra. Shear}}{\text{Stress}}$ (For 30,60,90 rev)

* Gyratory Shear Modulus (^{G}G) = $\frac{\text{Gyra. Shear}}{\frac{\text{(Max. Shear Strain)}}{10}}$ X 0.01745

* Gyratory Compression Modulus (E_G) = 2 X ^{G}G X (1 + μ)

* Gyratory Compression Strain (ϵ) = $\frac{\text{Vert. Pressure}}{E_G}$

* Temp. (^{o}C) = $\frac{9}{5}$ + 32 (^{o}F)